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The Afterglows of *Swift*-era Gamma-Ray Bursts. II. Short/Hard (Type I) vs. Long/Soft (Type II) Optical Afterglows

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ABSTRACT

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We use a large sample of Gamma-Ray Burst (GRB) afterglow and prompt emission data to compare the optical afterglows (or the lack thereof) of "short/hard" Type I GRBs (those that are assumed not to be due to the death of massive stars, but, e.g., merger of compact objects) with those of "long/soft" Type II GRBs (those due to the core collapse of massive stars). In comparison to the afterglows of Type II GRBs, we find that those of Type I GRBs have a lower average luminosity and show a larger intrinsic spread of luminosities. From late and deep upper limits on the optical transients, we establish limits on the maximum optical luminosity of any associated supernova, confirming older works and adding new results. We use deep upper limits on Type I GRB optical afterglows to constrain the parameter space of possible Mini-SN emission associated with a compact-object merger. Using the prompt emission data, we search for correlations between the parameters of the prompt emission and the late optical afterglow luminosities. We find trends between the bolometric isotropic energy release and the optical afterglow luminosity at a fixed time after trigger, and between the host offset and the luminosity, bit no significant trend between the isotropic energy release and the duration of the GRBs. We also discuss three anomalous GRBs, GRB 060121, GRB 060505, and GRB 060614, in the light of their optical afterglow luminosities.

Subject headings: gamma rays: bursts

1. INTRODUCTION

It has long been known that Gamma-Ray-Bursts (GRBs) come in (at least) two classes: Those typically lasting two seconds or less and having hard prompt emission spectra (short/hard GRBs) and those lasting typically longer than two seconds and having softer prompt spectra often showing strong hard-to-soft spectral evolution (long/soft GRBs) (Kouveliotou et al. 1993; Ford et al. 1995). The long/soft GRBs have been related spectroscopically (Galama et al. 1998; Hjorth et al. 2003a; Stanek et al. 2003; Malesani et al. 2004; Pian et al. 2006) to the deaths of massive stars, the so-called collapsar model (Woosley 1993) (for a recent review, see Woosley & Bloom 2006), and it was proposed that all long GRBs are accompanied by photometric supernova signatures (Zeh et al. 2004). The short/hard GRBs have been more enigmatic, as they are rarer and harder to localize. The most favored model is the merger of two compact objects, i.e. two neutron stars or a neutron star and a black hole (Blinnikov et al.

1984a,b; Paczyński 1986; Goodman 1986; Eichler et al. 1989)[1].

While there have also been extremely intense short/hard GRBs, such as GRB 841215 (Laros et al. 1985), GRB 930131 (e.g., Kouveliotou et al. 1994), and GRB 031214 (Hurley et al. 2003), the true breakthrough in the observations only came with the *Swift* satellite (Gehrels et al. 2004) and its discovery of well-localized afterglows in the X-ray band (Gehrels et al. 2005), as well as the *HETE-2* localization of GRB 050709. These lead to identifications in the optical (Hjorth et al. 2005b; Fox et al. 2005b; Covino et al. 2006) and radio (Berger et al. 2005b) bands, thus allowing for the first time an association between some short/hard GRBs and galaxies at moderate redshift that show no evidence of recent star-formation (Gehrels et al. 2005; Barthelmy et al. 2005a; Berger et al. 2005b). Thus, at least some short/hard GRBs must stem from a different progenitor class than long/soft GRBs, and several lines of evidence favor the compact object merger models (e.g., Fox et al. 2005b; Barthelmy et al. 2005a; Berger et al. 2005b). For recent reviews on short/hard GRBs, see Nakar (2007) and Lee & Ramirez-Ruiz (2007).

Further observations showed that the classic short/hard vs. long/soft dichotomy could not hold. Observations of early, soft, extended emission bumps and late X-ray flares in the afterglows of short/hard GRBs (Villasenor et al. 2005; Fox et al. 2005b; Barthelmy et al. 2005a; Campana et al. 2006) showed that even for compact object mergers, the central engine must be active for much longer time than previously thought. The situation became even more complex when two temporally long GRBs at low redshift were discovered which showed no evidence for accompanying supernovae, GRBs 060505 and 060614 (Della Valle et al. 2006a; Fynbo et al. 2006; Gal-Yam et al. 2006; Ofek et al. 2007a). GRB 060614, with $T_{90} = 102$ s, was clearly a long GRB but showed (Gehrels et al. 2006), next to the missing supernova, another clear sign of typical short/hard GRBs, negligible spectral lag between different energy bands of the prompt emission (Norris & Bonnell 2006). Zhang et al. (2007a) showed that it was possible to "transform" the prompt emission light curve of GRB 060614 into a light curve strongly resembling that of GRB 050724 (short, hard spike, long, faint and soft emission tail) simply by reducing the luminosity of the GRB. This lead to the idea of a new classification scheme for GRBs (Zhang 2006; Gehrels et al. 2006; Zhang et al. 2007a): In analogy to Type Ia and Type II supernovae, GRBs can be classified

[1]Note that we do not consider the "superflares" of Soft Gamma-Repeaters (SGRs) in this work, which have also been suggested as a source for part of the short GRB population (e.g., Hurley et al. 2005; Palmer et al. 2005). While Tanvir et al. (2005) showed that a significant number of BATSE short GRBs originate in the local universe, only two well-localized short GRBs, GRB 051103 and GRB 070201, are considered to be SGR flares in nearby galaxies (Ofek et al. 2006; Frederiks et al. 2007; Perley & Bloom 2007; Golenetskii et al. 2007a; Hurley et al. 2007; Abbott et al. 2007; Ofek et al. 2007b).

as Type I events (merger-induced, no supernova, can be found in all types of galaxies) and Type II events (collapsar-induced, associated with broad-lined Type Ic supernovae, found only in galaxies with high specific star-formation). This definition is not based on a single observed quantity (such as the location in a $T_{90}-$hardness diagram), and thus it is, in some cases, not possible to clearly state if a GRB is of Type I or II. We will adopt this terminology, and will use several observed indicators to separate the Type I and Type II samples. Also, we will later point out some shortcomings of the original definition. For an even more radical approach toward GRB classification based on physical progenitor models, see Bloom et al. (2008).

In a companion paper (Kann et al. 2007, henceforth Paper I), we compiled optical light curves of *Swift*-era Type II GRBs and compared them with those of a pre-*Swift* sample (Kann et al. 2006a, henceforth K06). We found that the two samples are very similar, and that, intrinsically, the afterglows had comparable luminosities. Therefore, it is justified to treat all afterglows as one large, coherent sample. In this work, we have compared the Type I GRB afterglows (which often only consist of non-detections and thus upper limits) with this large sample of Type II GRBs afterglows. The Type I GRB afterglow sample and the selection criteria, as well as the methods for modeling supernova contributions, are described in § 2.1. Using the method described in K06, all GRB afterglow light curves have been shifted to a common redshift, allowing a direct comparison of the afterglow luminosities of Type II and Type I GRBs. This allowed us to find the luminosity distribution of Type I GRB afterglows (§ 3.2), place deep upper limits on accompanying supernova emission (§ 3.3), and put constraints on the parameter space of heavy-element- and neutron-decay driven "mini-supernovae" as proposed by (Li & Paczyński 1998a,b, henceforth LP98ab), and (Kulkarni 2005, henceforth K05) (§ 3.4). We discuss our results in § 4. Furthermore, using the derived bolometric energetics of our Type I and Type II GRB samples, we search for correlations between the parameters of the prompt emission and the afterglow luminosities derived at a fixed rest-frame time § 4.3. A summary and conclusions are given in § 5.

In our calculations we assumed a flat universe with matter density $\Omega_M = 0.27$, cosmological constant $\Omega_\Lambda = 0.73$, and Hubble constant $H_0 = 71$ km s^{-1} Mpc^{-1} (Spergel et al. 2003).

2. DATA GATHERING AND ANALYSIS

2.1. Selection Criteria for the Type I GRB Afterglow Sample

As has been stated in the introduction, the "Type I and Type II" nomenclature is based on different observational quantities, not all of which are as easily accessible as T_{90}, the duration, in the observer frame, during which the GRB emits 90% of its fluence, starting after the first 5 % and extending to 95% (Kouveliotou et al. 1993). For this paper, we took a relatively open approach toward the sample selection. Donaghy et al. (2006) outline different criteria for deciding whether a GRB belongs to the "merger population" or the "collapsar population". Taking into account our complete sample, we focused on deciding which GRBs are probably Type I. Any remaining GRBs are then part of the Type II sample, without any controversial evidence that they might belong to the merger-population[2].

Most GRBs in this paper that are classified as Type I GRBs also fulfill the "classical" T_{90} definition out of the BATSE era (Kouveliotou et al. 1993). None of the GRBs in the Type II sample in Paper I have $T_{90} \leq 2$ s, although a few are just beyond the limit (e.g., XRF 050416A, which is an X-Ray Flash and has an associated photometric supernova, Soderberg et al. 2007). Those that are longer than $T_{90} = 2$ s have other indicators that put them into the Type I class. Norris & Bonnell (2006) propose that a strong indicator for a merger-population event is a negligible spectral lag between different energy bands, i.e. Type I GRBs do not follow a lag-luminosity correlation (Norris et al. 2000). Furthermore, Norris & Bonnell (2006) propose that certain BATSE GRBs that had been classified as "long" are indeed Type I GRBs, consisting of a short (usually ≤ 2 s) single spike or series of spikes (the Initial Pulse Complex, IPC), followed by a long, usually soft and faint Extended Soft Emission Component (ESEC). This link was made due to several *Swift* GRBs showing this characteristic light curve shape, with the classic example being GRB 050724, which was a clear Type I event due to its association with an old stellar population (Barthelmy et al. 2005a; Berger et al. 2005b; Gorosabel et al. 2006). Since we expect no or only very little light contribution from the decay of radioactive elements in the light of a Type I GRB afterglow (Hjorth et al. 2005a, and references therein), a final criterium is no detected SN emission to very deep limits several weeks after the GRB. GRB 060614 is a Type I GRB according to these criteria, in spite the very long T_{90}. GRB 060505, on the other hand, is a very special case, while the SN limits are deeper than for any other GRB ($M_R \gtrsim -10.5$ mag, Ofek et al. 2007a, this work), it has recently been shown to have significant spectral lag (McBreen et al. 2008). For reasons detailed later (§ 4.4), we will keep it in the Type I sample and discuss it

[2]We refer to Paper I and references therein on the possibility of further subclasses within the collapsar population, like intermediate GRBs and local low-luminosity GRBs.

in this paper. Details on all GRBs in our sample can be found in § A, where we also list the sources of the data used in this study.

In summary, our selection criteria are:

- $T_{90} \lesssim 2$ s and a hard spectrum with a high peak energy ("classical" short/hard GRB definition, we thus do not consider the sometimes short but very soft XRFs)
- and/or an IPC+ESEC prompt emission shape combined with negligible spectral lag (we thus do not consider "long" GRBs with negligible spectra lag like GRB 050717, Krimm et al. 2006)
- and/or the lack of a supernova down to deep, late limits for low-redshift events where it is known that dust extinction would not suppress supernova emission (this includes GRB 060505, GRB 060614 is also adressed by the second point)

2.2. Type I GRB Afterglow Light Curves

In almost all cases, no optical afterglows were discovered, so that only upper limits are available, either ground-based or by *Swift* UVOT. In order to maximize the available light curve information for our study, we transformed the data of all filters to the R band (after correcting for the individual foreground extinction for each GRB and each filter, Schlegel et al. 1998) by making the following assumptions: First, we assumed that the intrinsic spectral slope of the optical/NIR afterglow of each GRB is $\beta = 0.6$, unless the data were sufficient to measure it. In the standard fireball model[3], if the cooling frequency ν_c lies blueward of the optical bands, it is $\beta = (p-1)/2$ (e.g., Sari et al. 1998; Zhang & Mészáros 2004; Piran 2005, and references therein), with the canonical value $p = 2.2$ (Kirk et al. 2000; Achterberg et al. 2001), implying $\beta = 0.6$. Observations of Type II GRB afterglows show that this situation has the highest probability (K06), and the mean and median values of the complete sample of Paper I are almost exactly 0.6. While we caution that it has been shown that p is not universal (K06, Shen et al. 2006; Starling et al. 2008), and that ν_c can also lie redward of the optical bands (e.g., the case of GRB 060505, § A), our assumption should be valid in the majority of cases. The influence of a different spectral slope on the shift

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[3]While Type I GRBs clearly derive from a different type of progenitor as Type II GRBs, most of the physics behind the GRB and the afterglow are expected to be identical, i.e., a hyperaccreting accretion torus around a black hole which powers an ultrarelativistic fireball that propagates into the external medium. The viability of both neutron star-neutron star and neutron star-black hole mergers to create Type I GRBs has been shown in numerical simulations (e.g., Rosswog et al. 2003; Aloy et al. 2005; Rosswog 2005; Oechslin & Janka 2006).

dR_C § 2.3 is dependent on redshift. E.g., for $z = 0.2$, $\Delta dR_C = 0.3$ mag between $\beta = 0.5$ and $\beta = 1.1$, for $z = 0.8$, it is only $\Delta dR_C = 0.07$ mag. For the luminosity distribution, these small differences are not critical. Our second assumption is that the observed SED is unaffected by wavelength-dependent extinction through dust in the GRB host galaxies. As merger-induced events are typically expected to occur far from star-forming regions (but see, e.g., Belczynski et al. 2006; Dewi et al. 2006; van den Heuvel 2007), this assumption is reasonable (see Table 1). We caution, however, that one Type I GRB afterglow SED, that of GRB 050709, seems to show line-of-sight extinction even though the GRB is located in the outskirts of its host galaxy (Ferrero et al. 2007). In those cases where no afterglow has been detected and we have upper limits only, we choose successively deeper limits, as the afterglows are not expected to rebrighten significantly and follow a typical monotonic decay (see Fig. 1).

Many Type I GRBs do not have measured redshifts. So far, no absorption spectroscopy of a Type I GRB afterglow has been successful (cf. Stratta et al. 2007), so that redshifts can only be determined from host galaxy spectroscopy. In some cases, no galaxies (or only extremely faint ones) are found in the *Swift* XRT error circles, and the GRBs are instead assumed to be associated with bright nearby galaxies, such as in the case of GRB 050509B (Gehrels et al. 2005) (localized in the outskirts of a bright elliptical galaxy), GRB 060502B (Bloom et al. 2007a) and GRB 061201 (Stratta et al. 2007), or galaxy clusters, as for GRB 050911 (Berger et al. 2006a). Finally, if no association can be made at all, we choose a redshift $z = 0.5$, which is the (rounded) median value of all measured redshifts we consider secure. In two cases (GRB 051227 and GRB 060313), we choose $z = 1$, as the host galaxies of these GRBs (localized to subarcsecond precision through their optical afterglows) are exceedingly faint ($R \gtrsim 26$) and thus resemble the hosts of Type II GRBs (although we caution that we have no detailed information on properties such as star-formation rates etc.). In an earlier version of the draft, we also assumed $z = 1$ for GRB 070714B, as it shows several similarities to GRB 060313 (§ A). In the meantime, the redshift has been measured from host galaxy spectroscopy to be $z = 0.92$ (Graham et al. 2007; Cenko et al. 2008), very close to our initial estimate. We caution that while there is evidence that these GRBs do not lie much beyond $z = 1$ (e.g., the detection of the afterglow of GRB 060313 in all UVOT filters, Roming et al. 2006), they may lie significantly closer, with their host galaxies lying at the faint end of an as yet unknown luminosity distribution.

2.3. Shifting Light Curves to a Common Redshift

With knowledge of the redshift z, the extinction-corrected spectral slope β and the host galaxy rest frame extinction A_V, we can use the method described in K06 to shift all Type I GRB afterglows to a common redshift of $z = 1$, corrected for extinction along the line of sight. As stated in § 2.1, we do not have β and A_V for most Type I GRB afterglows, and in some cases, even z is unknown. Thus, on many Type I GRB afterglows, we can not derive results analogous to the Type II GRB afterglows (Paper I), but have to view them as an ensemble. Compared with the true but unknown values for the parameters needed for the magnitude shift dR_C, the magnitudes or upper limits of some GRBs may be fainter or brighter. The effect is stronger for low redshifts, for $z = 0.2$ in comparison to $z = 0.5$, it is $\Delta dR_C = 2.1$, for $z = 0.8$ in comparison to $z = 0.5$, it is $\Delta dR_C = 1.1$. Still, in a statistical sense, the effect will not be strong as we expect the true redshifts of the GRBs to be distributed relatively evenly around $z = 0.5$.

2.4. Determining Upper Limits on a Supernova Light Component

Using the method described in § 2.3, we have shifted Type I GRB afterglow light curves to a redshift of $z = 0.1$. In most cases, the shift to $z = 0.1$ is smaller in z-space than a shift to $z = 1$, implying a smaller uncertainty through the unknown β. Another reason for performing this analysis at $z = 0.1$ and not at $z = 1$ is that at the latter redshift, the observer frame R_C band of the supernova template is highly insecure due to strong UV blanketing. Our sample consists of those Type I GRBs that have a known redshift (which, in some cases, is derived only from associating the GRB with a nearby bright galaxy or a cluster) and late detections/upper limits: GRB 050509B, GRB 050709, GRB 050724, GRB 050813, GRB 050906, GRB 051221A, GRB 060502B, GRB 060505, GRB 060614 (the latter two being the "SN-less long GRBs") and GRB 061201. We then compare the detections/upper limits with the template light curve of SN 1998bw (Galama et al. 1998)[4], see Zeh et al. (2004) for details of the method and descriptions of the parameters k and s, which measure the GRB-SN luminosity in units of the luminosity of SN 1998bw at peak and the light curve stretching in comparison to the SN 1998bw light curve, respectively. In our comparison, we conservatively assume that the late optical emission from the Type I GRBs is due only to supernova light and there is no contribution from afterglow emission. In the case of deep (host-galaxy subtracted) detections, we fit the template to pass through the brighter 1σ

[4]For the world model used here, SN 1998bw was 0.19 mag less luminous than given in Galama et al. (1998).

error bar of the faintest data point, and in the case of an upper limit, we fit the template to pass through the most restrictive upper limit. As we have no information at all about the stretch factor s, we assumed $s = 1$ in all cases. If the stretch factor is smaller than SN 1998bw, such as XRF 060218/SN 2006aj (Ferrero et al. 2006) or the photometric SN bump of XRF 050824 (Sollerman et al. 2007) the luminosity limit typically would be slightly less constraining. Our fitting then results in a value of the luminosity factor k, e.g., $k = 0.1$ implies a supernova that has 0.1 times the peak luminosity of SN 1998bw in the same band at the same redshift. As there have been no signs of supernova bumps in the light curves of Type I GRB afterglows, our k values can be seen as conservative upper limits on any supernova contribution.

2.5. The Mini-Supernova/Macronova Model

The mini-SN model was introduced by LP98ab as a potential observational consequence following the merger of two compact objects (NS + NS or NS + BH). During the merger, neutron star matter at nuclear densities can be ejected at subrelativistic velocities, condensing into neutron-rich nuclei which rapidly decay, yielding a similar heating source as classical radioactivity-driven supernovae.

From the numerical point of view the analytical solutions given in LP98ab are easy to handle and, therefore, we used them in our study. Basically, the LP98ab model depends on three free parameters, the ejected mass $M_{\rm ej}$ which is assumed to be identical to the radiating mass, the expansion velocity v of the ejected matter, which is assumed to be independent of time, and the fraction f of rest mass energy that is transformed into internal heat of the ejecta. A more detailed description can be found in § B.

LP98ab considered two cases of decay laws for the heating source, an exponential-law decay and a power-law decay. They found that in both cases for, e.g., f=0.001 bright SNe are predicted with bolometric peak luminosities up to 10^{44} erg/s, or even higher. Ten years later, in the *Swift* era, it has become clear however that such bright SNe following short bursts are not seen (Fox et al. 2005b; Hjorth et al. 2005a).

3. RESULTS

3.1. Observed Type I GRB Afterglows

The light curves of the afterglows of our Type I GRB sample are presented in comparison with the pre*Swift* and *Swift*-era Type II GRB afterglow light curves (Paper I) in Fig. 1. Upper limits are marked with downward pointing triangles connected by straight lines, while detections are squares connected with splines. All the afterglow data have been corrected for Galactic extinction (which is often small) and in some cases, the contribution of the host galaxy was subtracted (§ A). We have labeled only a few special afterglows, as this would otherwise decrease legibility. It is visible immediately that observationally, the optical afterglows of Type I GRBs are much fainter than those of Type II GRBs. Most optical afterglows are not detected at all, to upper limits that would have clearly detected all Type II GRB afterglows in this sample[5]. This is especially the case for early times (<0.01 days), where only a few Type II GRB afterglows (e.g. GRB 050820A, XRF 050416A, GRB 070110) are fainter than most limits.

The most constraining upper limits are on GRB 050509B, which was observed rapidly by ROTSE (Rykoff et al. 2005) and RAPTOR (Woźniak et al. 2005), an upper limit of $R_C > 18.75$ is found after just 30 seconds. Furthermore, Bloom et al. (2006) give an upper limit $R_C > 24.3$ at only 0.09 days after the GRB, almost four magnitudes deeper than needed to detect any Type II GRB in the sample of Paper I. The faintest Type I afterglow in our sample is that of GRB 051227, discovered by the VLT (Malesani et al. 2005a) and seen to decay very rapidly, possibly due to post-jet-break decay. The only afterglow of a Type I GRB (and a controversial one at that) that is comparable to the typical Type II GRB afterglows is that of GRB 060614 (Della Valle et al. 2006a; Fynbo et al. 2006; Gal-Yam et al. 2006; Mangano et al. 2007). This afterglow starts out faint but rises to a peak at about 0.25 days, followed by a typical afterglow decay that includes a jet break (Mangano et al. 2007).

3.2. The Luminosity Distribution of Type I GRB Afterglows

After shifting all afterglows to $z = 1$ (Paper I), we can compare the afterglows of Type I and Type II GRBs. The results are shown in Fig. 2, the labeling is identical to that in Fig. 1. Magnitude shifts dR_c and absolute magnitudes M_B at one day after the

[5]We caution that the Type II sample of Paper I is biased toward (observationally) bright afterglows due to the sample selection criteria. There have been dark Type II GRBs in the *Swift*-era that are also undetected optically to limits similar to the Type I GRB afterglow limits.

burst are given in Table 2. It is immediately apparent that while the afterglows of Type II GRBs still tend to cluster in luminosity space (K06, Liang & Zhang 2006; Nardini et al. 2006, 2008, Paper I), the afterglows of Type I GRBs spread even further apart. At 0.1 days, the total span is greater than 11 magnitudes, from GRB 060121 at 17th magnitude (assuming $z = 4.6$, de Ugarte Postigo et al. 2006) to an upper limit on the afterglow of GRB 050509B at fainter than 28th magnitude. Assuming $z = 1.7$ for GRB 060121, the spread is about 1.5 magnitudes less. At the same time, the spread of Type II GRB afterglows is only about 6 magnitudes, from 14th to 20th magnitude, and these afterglows tend to cluster even more strongly at later times. The variance of the complete Type II GRB afterglow sample of Paper I is 2.6 magnitudes, whereas the variance of the Type I GRB afterglow detections is 6.3 magnitudes (3.1 magnitudes without GRB 060121), that of the upper limits 4.0 magnitudes. For the complete Type I GRB afterglow sample (detections and upper limits, but without GRB 060121), the variance is at least 3.6 magnitudes. Furthermore, the Type I GRB afterglows are much fainter than those of Type II GRBs, as has been predicted by Panaitescu et al. (2001). GRB 060121, which probably lies at high redshift and is strongly collimated (de Ugarte Postigo et al. 2006; Levan et al. 2006), is comparable to typical Type II GRB afterglows if $z = 4.6$, and comparable to faint Type II GRB afterglows if $z = 1.7$. The afterglow of the extremely energetic GRB 060313 (Roming et al. 2006), assuming $z = 1$, is also comparable to the faintest Type II GRB afterglows of the sample. At about one day, the afterglow of GRB 060614, by far the brightest observed Type I GRB afterglow, is half a magnitude fainter than the afterglow of GRB 070419A (Paper I), and then it becomes even fainter rapidly. Assuming the association with a galaxy at $z = 0.111$ (Berger 2006b; Stratta et al. 2007), the afterglow of GRB 061201 has a magnitude of $R_C \approx 25.5$ just a few minutes after the GRB, which is about 11 magnitudes fainter than the typical early Type II GRB afterglows. The afterglow of GRB 060505, for which it is unclear if it is a Type I GRB (Ofek et al. 2007a) or a Type II GRB (Fynbo et al. 2006; Thöne et al. 2008; McBreen et al. 2008), is here seen to be about 4 magnitudes fainter than the faintest Type II GRB afterglows, but well comparable to the other Type I GRB afterglows or upper limits thereon. It is thus clearly not a classical Type II GRB, but also not of the subluminous Type II family, such as GRB 980425 (Galama et al. 1998), GRB 031203 (Sazonov et al. 2004; Soderberg et al. 2004; Malesani et al. 2004) and XRF 060218 (Campana et al. 2006; Pian et al. 2006; Soderberg et al. 2006b), as these GRBs, while possessing very faint afterglows, were also accompanied by energetic supernovae. We refer to § 4.4 for a deeper discussion on this GRB.

A histogram of the absolute magnitudes M_B (at one day after the burst assuming $z = 1$) is shown in Fig. 3. The luminosity distribution of *Swift*-era Type II GRB optical afterglows are very similar to the sample of K06 (Paper I). The Type I GRB afterglows which are

detected are found to be five magnitudes fainter in the mean, it is $\overline{M_B} = -18.2 \pm 0.7$, thus, roughly a factor of 100 less luminous than Type II GRB afterglows. If GRB 060121 is removed, the mean absolute magnitude goes down to $\overline{M_B} = -17.3 \pm 0.4$.

We note that in the sample with detections, there are four GRBs with assumed redshifts. But two of these, GRB 051227 and GRB 060313, were assumed to lie at $z = 1$. Almost all other Type I GRBs with redshifts are closer than this, so it is more likely that the true redshifts of these two GRBs will be $z < 1$ than $z > 1$, making their absolute magnitudes even fainter and the strong bimodality of Type I and Type II GRB afterglows even more secure. Also, we note that one of the Type II GRB afterglow samples of Paper I, the "Bronze Sample", is not corrected for host extinction, as SED information was lacking. Therefore, the luminosities of those afterglows are lower limits, any extinction correction would make them brighter, which would also strengthen the bimodality. For the upper limits, the percentage of GRBs with an estimated redshift ($z = 0.5$ in all cases) is higher, and thus the upper limit on the mean magnitude, which is even lower than the mean magnitude of the detections, $\overline{M_B} \geq -17.0 \pm 0.5$, is to be taken with caution. Taking all Type II GRB afterglow absolute magnitudes (58 data points) and all Type I GRB afterglow absolute magnitudes (28 data points), including the upper limits, a KS test (Press et al. 1992) shows that the two samples are inconsistent with being drawn from the same distribution with a high significance ($P = 8 \times 10^{-10}$). (*TBD Not yet final value*). As we do not expect the basic fundamental principles of afterglow emission to be different for Type II and Type I GRB afterglows (i.e., both are external forward shock emission from a relativistic fireball), the reason for this bimodality must lie elsewhere, as will be discussed below.

3.3. Constraints on SN 1998bw Light in Type I GRB Afterglows

The appearance of classical SN light, both photometrically and spectroscopically, in a GRB afterglow is the main observational evidence for the origin of the burst being a collapsing massive star. Its non-detection within about the first 2 weeks down to deep luminosity limits is therefore usually considered as a strong argument in favor of the identification of the burst under consideration as a Type I GRB, especially if one considers Type I GRBs those that do not originate from the deaths of massive stars. Only recently has it become obvious that other explosion channels of single stars that do not produce bright SNe may be realized, namely stars that collapse more or less directly to a black hole (Fryer et al. 2006, 2007). This has been suggested as an explanation for the "SN-less long GRBs" GRB 060505 and GRB 060614 (Fynbo et al. 2006; Gal-Yam et al. 2006; Della Valle et al. 2006a; Thöne et al. 2008; McBreen et al. 2008) and has been predicted based on theoretical grounds even before the

detection of these two events (Woosley 1993; Arnett 1996; Fryer et al. 2006; Nomoto et al. 2007; Tominaga et al. 2007; Fryer et al. 2007).

The results from our analysis of supernova limits, including GRB 060505 and GRB 060614, are shown in Fig. 4 and given in Table 2. The limits for GRB 051221A and GRB 050813 are not very strict, as both GRBs lie at a redshift ($z = 0.5 - 0.7$) where it also becomes challenging to detect the supernova signature in Type II GRB afterglows (Zeh et al. 2004). Furthermore, in both cases, observations were not extended to a time when a hypothetical accompanying supernova would have probably peaked (assuming a similar rise time as SN 1998bw). The limits for GRB 060614, GRB 060502B, GRB 050509B, GRB 050709, GRB 060505 and GRB 061201 are much stricter, and fainter than any Type II SN known (not to mention broad-lined Type Ic SNe; Ferrero et al. 2006, and references therein)[6]. The limits for GRB 050724 and GRB 050906 are intermediate between the two extremes, fainter than broad-lined Type Ic SNe, but still comparable to fainter Type II SNe (note that the redshift of GRB 050906 is not secure.). Our limits are in accordance with those found by other authors for GRB 050509B (Hjorth et al. 2005a; Bersier et al. 2005), GRB 050709 (Hjorth et al. 2005b; Fox et al. 2005b), GRB 050724 (Malesani et al. 2007b), GRB 050906 (Levan et al. 2007b), GRB 050813 (Ferrero et al. 2007), GRB 051221A (Soderberg et al. 2006a), GRB 060505 (Ofek et al. 2007a; Fynbo et al. 2006) and GRB 060614 (Gal-Yam et al. 2006; Fynbo et al. 2006; Della Valle et al. 2006a). The limits for GRB 060502B and GRB 061201 stated here are derived for the first time in this paper. This compilation further substantiates the observation that Type I GRBs are not associated with the deaths of massive stars and their accompanying supernovae and must derive from progenitors that produce only very small amounts of ^{56}Ni, such as the mergers of compact objects. The missing bright late-time SN signal of Type I GRBs is thus a substantial phenomenological difference compared to the late-time evolution of Type II GRBs (see also Hjorth et al. 2005a; Fox et al. 2005b). On the other hand, even the very strict limit, $M_R \gtrsim -10.5$, on a supernova accompanying GRB 060505 (Ofek et al. 2007a, this work), which yield M(^{56}Ni) $\lesssim 1 \times 10^{-4}\ M_{\odot}$, cannot exclude a collapsar with a very low jet energy deposition (Nomoto et al. 2007; Tominaga et al. 2007). Furthermore, the less constraining upper limits cannot exclude supernovae similar to the faintest local core-collapse events (cf. Richardson et al. 2002; Pastorello et al. 2004). Still, there must exist a broad gap in peak luminosity between these faint SNe (if they exist at all) and the traditional SNe associated with Type II GRBs.

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[6]We point out that it has been claimed by Pastorello et al. (2007) that the "luminous red nova" M85 OT2006-01 (Kulkarni et al. 2007; Rau et al. 2007; Ofek et al. 2008) may actually be an extremely subluminous Type IIp SN with $M_R = -12.1$ during the plateau. Such an event would indeed not be detectable in almost all late Type I GRB afterglow light curves, except for GRB 060505, but here, see § 4.4.

It must be stressed that only in two cases detections of the optical transient at the time of the suspected SN maximum at $t > 10$ days have been reported in the literature (for GRB 050709 and GRB 060614; even though, after host subtraction, with a large error bar for the latter), but no late-time follow-up observations weeks after the suspected SN peak have been published so far. This leaves open the question if this positive detection was the late afterglow light or in fact an underlying faint SN component, even though the error bar is small enough for GRB 050709 only to tackle this question seriously. In all other cases only upper limits are available at the suspected SN maximum around $(1+z) \times 15...20$ days after the corresponding burst, if at all.

Clearly, the upper limits we can set will be misleading if the light curve evolution of any kind of a SN following a Type I event differs substantially from the one of GRB-SNe of Type II bursts, i.e. with respect to peak time and stretch factor. This brings us to the mini-SN model.

3.4. Constraints on the Mini-Supernova/Macronova Model

3.4.1. Power-law Decay

We first consider the power-law decay model, which was considered by LP98ab as the most likely case. LP98ab demonstrated that, depending on the chosen model parameters, a mini-SNe can peak at much earlier times than a normal core-collapse supernova. Therefore, given the currently available data base (Fig. 4), one has to distinguish between those Type I GRBs with and those without detected early afterglow light. For example, a relatively bright mini-SN peaking at, say, R=22 about 0.5 days after the burst could have been escaped detection in the early light curve of the afterglow of GRB 051221A. Faint mini-SNe could also be underlying the afterglow light curves of GRB 050709 and GRB 060614 without being recognized because of lack of spectral information.

Much tighter constraints can be set for those Type I GRBs with deep upper limits. Figure 2 shows that up to about 2 weeks after the event, the observed upper limits on any optical afterglow following GRB 050509B are the deepest limits for any Type I GRB obtained so far. In addition, the very likely association of GRB 050509B with a giant elliptical galaxy (Gehrels et al. 2005) and the offset from this host makes it unlikely that the faintness of the afterglow/mini-SN was due to internal extinction in the host galaxy. For this burst, the strongest constraint comes from the observed upper limit around 0.96 days after the event ($R > 23.7$; note that this magnitude limit includes a transformation to a redshift of z=0.1; Fig. 4). Figure 5 shows the allowed parameter space (f, M) (see § 2.5 for the definitions of

these quantities) for any mini-SN following GRB 050509B, assuming an expansion velocity of $\beta = v/c = 1/3$ (following LP98ab) and a matter opacity identical to Thomson scattering. If, within this model, $\log f$ lies somewhere between -3 and -5 then for this event the ejected mass must have been less than 0.001 $M_\odot$.

3.4.2. Exponential-law Decay

K05 discussed in detail the model of an explosion where the decay of free neutrons is the internal heating source. Moreover, by adding the contribution of the thermal pressure to the equation describing the expansion of the ejected envelope, K05 generalized in some way LP98ab's approach. Unfortunately, no analytic solution is then known.

Following K05 we assumed that the energy source decays according to an exponential law with a half life time of 10.4 min but we fixed $v/c = 0.3$. The evolution of the neutron-rich ejecta is then photon pressure dominated so that the analytic solutions given in LP98b (their Eq. 20) can be used.[7] For the parameter range $(f, M_{\rm ej})$ investigated here the ejecta is usually very hot ($> 10^4$ K) at the time of the peak of the bolometric luminosity. The luminosity in the optical bands then peaks at later time (see also K05, their Figures 5 and 6), usually around 1 day. Unfortunately, for small ejected masses the envelope becomes rapidly optically thin so that our approach to calculate the optical luminosity via the assumption of black body radiation (see § B concerning the method) becomes less secure in such cases.

Figure 6 shows the allowed parameter range $(f, M_{\rm ej})$ again based on the observed upper limit of $R >$23.7 at 0.96 days for any afterglow that followed GRB 050509B. For $f = 3 \times 10^{-4}$, as it follows from the calculations given in K05 (their equation 43), the ejected mass cannot have been larger than about 0.002 $M_\odot$. This constraint on $M_{\rm ej}$ is still in the lower range of the results obtained by numerical studies of neutron star mergers (cf. Oechslin et al. 2007).

4. DISCUSSION

4.1. The Afterglow Luminosities of Type I GRB vs. Type II GRB Afterglows

Several years before the first detection of a Type I GRB afterglow, Panaitescu et al. (2001) predicted that the discovery and follow-up of Type I GRB afterglows would be a

[7] Note that this analytic solution is not included in the published Letter, LP98a, but only included in the on-line available preprint version, LP98b.

big observational challenge. Based on the observational fact that typical Type I GRBs show a fluence more than an order of magnitude smaller than typical Type II GRBs, they predicted that the afterglows should be 10 to 40 times fainter, with radio afterglows hardly detectable and X-ray afterglows giving the best chance for detection. Furthermore, a low density external medium, as might be expected from merger progenitor models, would further complicate the chances for follow-up, as would less collimated jets. Basically, their predictions have been observationally confirmed. We have shown, however, that the factor is around 100, not only 10 to 40. One reason for this discrepancy is that many *Swift*-detected Type I GRBs have up to orders of magnitude less isotropic energy release than the 5×10^{51} erg Panaitescu et al. (2001) used in their modeling. The additional detrimental effects of low density external media (e.g., Panaitescu 2006) and large jet opening angles (e.g., Grupe et al. 2006) have also been shown to play crucial roles[8]. Even very energetic Type I GRBs at redshifts comparable to typical Type II GRBs, such as GRB 060313 (Roming et al. 2006) and GRB 070714B (Graham et al. 2007; Cenko et al. 2008), have optical afterglows that are comparable to faint Type II GRB afterglows only. The predictions of Panaitescu et al. (2001) concerning radio and X-ray afterglows have also proven to be correct, as only two Type I GRBs have been detected in the radio (Berger et al. 2005b; Soderberg et al. 2006a), whereas most of those which *Swift* was able to slew to immediately have X-ray afterglows (e.g., Nakar 2007).

To access the reason of the faintness of Type I GRB optical afterglows, we use the standard external shock model (Mészáros & Rees 1997; Sari et al. 1998). For merger-like events, the circumburst medium is expected to have a constant density. With typical parameters, the optical band should satisfy $\nu_m < \nu_{opt} < \nu_c$, where ν_m and ν_c are the minimum injection synchrotron frequency and cooling frequency of relativistic electrons, respectively. The optical afterglow flux density in this regime is (Panaitescu et al. 2001)

$$F_\nu \propto \epsilon_B^{(p+1)/4} \epsilon_e^{p-1} E_{K,iso}^{(p+3)/4} n^{1/2} f_p D_L^{-2} \tag{1}$$

where $f_p \propto [(p-2)/(p-1)]^{(p-1)}$ (Zhang et al. 2007b). Other notations follow the convention of the standard afterglow model: $E_{K,iso}$ is the isotropic kinetic energy of the blastwave, n

[8]We caution that the jet opening angle only plays an important role in a comparative sense if a standard jetted energy reservoir is assumed (Frail et al. 2001; Bloom et al. 2003). With the discovery of both intrinsically subluminous (e.g., XRF 060218, Amati et al. 2007; Cobb et al. 2006a; Liang et al. 2007a; Pian et al. 2006; Soderberg et al. 2006b) and "superluminous" GRBs (e.g., GRB 050820A, GRB 050904 and GRB 070125, Cenko et al. 2006a; Tagliaferri et al. 2005; Frail et al. 2006; Chandra et al. 2008; Updike et al. 2008), the idea of a standard energy reservoir for Type II GRBs is untenable (see also Kocevski & Butler 2007; Liang et al. 2008). Furthermore, there is as yet only little evidence of a standard energy reservoir for Type I GRBs (e.g., Soderberg et al. 2006a).

is the circumburst medium density, ϵ_e and ϵ_B are the fractions of the shock internal energy carried by electrons and magnetic fields, respectively, p is the spectral index of the relativistic electrons, and D_L is the luminosity distance of the burst. The fainter afterglows of Type I GRBs are due to the combination of a lower fluence and a lower energy density as expected for the merger scenarios (Panaitescu et al. 2001). The derivation of Panaitescu et al. (2001) was based on two assumptions: Type I GRBs have similar radiative efficiency as Type II GRBs, and $E_{K,iso}$ of Type I GRBs is on average 20 times smaller than that of Type II GRBs. With the recent observations of Type I GRBs, it is clear that the first assumption holds, i.e. for a sample of Type I GRBs studied, the radiative efficiency is not very different from that of Type II GRBs (Zhang et al. 2007b; Nakar 2007; Berger 2007c). However, the second assumption, which was based on the fact that Type I GRBs have a ~ 20 times smaller fluence than Type II GRBs and the implicit assumption that both populations have a similar mean redshift, is no longer justified. It is now known that a large fraction of Type I GRBs are nearby, so that they are less energetic than previously expected, i.e. $E_{K,iso}$ is more like 100 times smaller than that of Type II GRBs. Leaving out the $E_{K,iso}/D_L^{-2}$ factor in eq.(1) which takes account for the fluence factor discussed by Panaitescu et al. (2001), there is an additional $\propto E_{K,iso}^{(p-1)/4}$ dependence. This accounts for another factor of $100^{0.3} \sim 4$ reduction of Type I GRB flux (assuming a typical value of $p \sim 2.2$) with respect to the estimate of Panaitescu et al. (2001). This is in agreement with the results presented in this paper. In some cases, an even lower density n (to be consistent with the intergalactic medium outside the host galaxy - as expected to happen for some short GRBs with large kick velocities) is needed to account for the faintness of the afterglows (Nakar 2007).

The larger spread of F_ν for Type I GRBs than Type II GRBs is less straightforwardly interpreted. Both types of GRBs should follow the same parameter dependences as shown in eq.(1)[9]. One has to argue that the scatter of the parameters is larger for Type I GRBs than Type II GRBs. One factor of F_ν scatter is due to that of $E_{\rm K,iso}$ (with a dependence of $\propto E_{\rm K,iso}^{(p+3)/4}$). The high-$z$ Type I GRB 060121 is an example that has a much larger $E_{\rm K,iso}$ than its low-z brethren. It may be highly collimated (de Ugarte Postigo et al. 2006), or may be related to a different progenitor from most other Type I GRBs. A second factor that causes the larger scatter of F_ν for Type I GRBs is the circumburst medium n (with a dependence $\propto n^{1/2}$). Since merger events can happen in all types of galaxies and either inside and outside the hosts, as suggested by the data, the ambient density could have a large scatter. While mergers inside star-forming galaxies may have a medium density

[9]In principle, some Type II GRBs may have a stellar wind medium (Chevalier & Li 1999). Analyses of Swift GRB X-ray afterglows however suggest that most bursts are consistent with a constant-density medium (Zhang et al. 2007b; Liang et al. 2007b).

comparable to that of Type II GRBs, those events outside the hosts (due to large kicks received during the births of one or two neutron stars in the system) could have a tenuous medium, which tends to give rise to a "naked" burst (e.g. La Parola et al. 2006). Another possibility that leads to a low density circumburst medium and a large offset without the need for high kick velocities are mergers in globular clusters (Grindlay et al. 2006; Salvaterra et al. 2008). A more speculative possibility is the scatter of shock parameters. While for Type II GRBs ϵ_B may be mainly determined by the post-shock instabilities that generate the in-situ fields (Medvedev & Loeb 1999), the existence of a pulsar wind bubble (for reviews, see e.g., Gaensler 2003; Slane 2007; Bucciantini 2007) before the merger events would introduce a background magnetic field which would be compressed by the shock to power synchrotron emission (for GRBs and pulsar wind nebulae, see Königl & Granot 2002; Guetta & Granot 2004). This extra complication may introduce a larger scatter of ϵ_B and hence F_ν (with a dependence $\propto \epsilon_B^{(p+1)/4}$). But the existence of such a bubble can be ruled out for all but the youngest merging systems, which are expected to make up only a small part of the population (e.g., Belczynski et al. 2006).

4.2. Supernova Light in Type I GRB Afterglows

Classical SN 1998bw light with its peak around 15...20$(1+z)$ days after a burst is still the clearest signature of a Type II event. Type I events, on the other hand, should not have such a pronounced SN signal and in fact it has never been found. The deepest limit obtained so far for a potential SN 1998bw component that followed a burst is for GRB 060505 with $M_R \gtrsim -10.5$.

As it has already been shown by LP98ab and K05, getting very deep upper limits between around some hours and 1 days after a short burst might provide the strongest constraints on extra light related to the ejecta from merging compact objects. For example, for certain models discussed here the current data set, given by the upper limits on an optical transient following GRB 050509B, already excludes a mass ejection of more than about 0.001 solar masses. Unfortunately, since the peak luminosity is proportional to $f\, M_{\rm ej}^{1/2}$ (LP98a, their Eq. 13) getting deeper flux limits basically means setting tighter constraints on f and not so much on $M_{\rm ej}$.

Given the very small signal strength we potentially might expect from a mini-SN or macronova, observing in white light, i.e. unfiltered, is perhaps the very best strategy at first. Since short bursts related to elliptical host galaxies are the best candidates for having faint afterglows, any additional signal might be best detectable or constrained in these cases.

Additional strong constraints on decay-driven light in Type I GRB optical transients would come from spectroscopy or broadband optical/NIR photometry. This would allow the detection of a component in the transient light that deviates from the expected afterglow synchrotron spectrum (which may be additionally affected by dust), or allow the placement of upper limits thereon. Acquiring such spectroscopy will be challenging, though. Thus far, only three Type I GRBs have had their afterglows detected within the first minutes after the GRB (GRB 060313, GRB 061201 and GRB 070714B), and in all cases, the early evolution was flat and the afterglow was fainter than 20th magnitude upon discovery. Only GRB 060614, for which the identification as a Type I GRB remains questionable, had an afterglow which was bright enough at observation time to allow 8m-class telescopes to obtain high S/N spectroscopy. This case illustrates a second quandary concerning the spectroscopy of Type I GRB afterglows, and the identification of absorption lines and thus unambiguous redshifts. The first spectrum of the afterglow of GRB 060614 contained no lines in emission or absorption (Fugazza et al. 2006), and a redshift could only be determined after the afterglow had faded enough to allow host galaxy emission lines to be detected (Price et al. 2006b). Even so, the association with the galaxy is somewhat controversial (Schaefer & Xiao 2006; Cobb et al. 2006b) due to the quite large offset from its host galaxy in terms of half-light radius or brightest pixel distribution (Gal-Yam et al. 2006), but this is based on *a posteriori* statistics, Gal-Yam et al. (2006) use HST imaging to determine a very low probability (6×10^{-6}) of a chance association. Indeed, it is this offset, and the associated low-density medium surrounding the progenitor, which is probably the source of the low column densities of any absorption lines. This may turn out to be a serious problem for the determination of absorption line redshifts, as the typical observed magnitudes of Type I GRB afterglows preclude the use of echelle spectroscopy, which is a better tool to detect low column density absorption lines. Thus, we conjecture that the first successful (i.e., high continuum S/N) spectroscopy of a Type I GRB afterglow will probably not yield usable absorption lines that allow a redshift determination. Indeed, Stratta et al. (2007) recently reported that spectroscopy of the afterglow of GRB 061201 revealed neither absorption nor emission lines, but pointing constraints limited the exposure time to one hour, and the S/N is low.

4.3. Energetics and Correlations

Our unique sample of Type I and Type II GRB afterglow luminosities allows us to look for correlations between different parameters. To achieve a comparison with the energies of the GRBs, we compile the fluences and Band function (or cut-off power law) parameters for our Type I GRB sample (Table 1) and add these parameters for the Type II GRB sample (Paper I). In total, our sample encompasses 30 Type I GRB events and 58 Type II GRB

events. Using the given spectral parameters and the redshifts, we derive k-corrections for the rest-frame bolometric bandpass of 1 to 10000 keV following the method of Bloom et al. (2001). Using the bolometric correction, the fluences and the luminosity distances, we then derive the bolometric isotropic energy $E_{iso,bol}$ for all GRBs.

4.3.1. The Bolometric Isotropic Energy vs. the Optical Luminosity

The plot of bolometric isotropic energy release (Table 1) versus the flux density of the afterglow at one day after the GRB assuming $z = 1$ (converted from Table 2) is shown in Fig. 7. This is an expansion of Figure 7 in Paper I. We differentiate between five data sets. All Type II GRB afterglows have detections and a secure redshift. In the case of Type I GRB afterglows, we differentiate between detected afterglows and upper limits, and between secure and insecure redshifts. Taking the complete data set, there is a clear trend visible. GRBs with larger isotropic energy output tend to have brighter optical afterglows at a fixed late time after the GRB, when possible additional early emission processes like reverse shock flashes contribute only negligibly. This trend is very similar to the one found by Berger (2007c), who compared the isotropic energies (without performing a k-correction) with the X-ray luminosities at a fixed datum, and it confirms the trend already seen in the Type II GRB afterglows alone (Paper I). At first glance, the Type I and Type II samples form a homogeneous sample, with the brightest and most powerful Type I GRBs (e.g., GRB 060121, GRB 060313, GRB 070714B) overlapping with the faintest Type II GRBs (e.g., GRB 060512, XRF 050416A, GRB 070419A, see Paper I). The Type II GRB afterglows have a very large scatter, e.g, the spread around $E_{iso,bol} \approx 10^{54}$ erg is almost a factor of 40 (four magnitudes), and in most cases, the errors on the flux density of the optical afterglows are very small. Without several low-luminosity events such as those mentioned before, no trend would be visible at all (Paper I). This large scatter is probably due to several underlying causes, with the diverse jet opening angles probably having the strongest impact. A large spread of circumburst densities may also play a role. An unweighted linear fit to the Type I GRB afterglows with detections and secure redshifts shows that while the slope is similar (from linear fits to the logarithmic quantities, we find slopes of 0.36 and 0.38 for Type II and Type I afterglows, respectively), the normalization is different. At 10^{50} erg, the difference in flux density is a factor 15^{+22}_{-9}; and 14^{+42}_{-11} at 10^{51} erg, where the two data clouds overlap. As discussed before, assuming the radiative efficiencies and blastwave physics to be similar for both central engine types (also, the jet opening angle distribution needs to be similar, it is as yet unclear if this is the case), this is an indication that the typical circumburst density around Type I GRB progenitors is lower than for collapsar-induced GRBs. As the normalization difference is $\propto n^{1/2}$, this implies that the typical ambient density around Type

I GRB progenitors is roughly a factor of ≈ 200 less, albeit with very large error margins (the range of 10 to several 1000). Still, a spread of efficiencies is possible (for a detailed analysis, see Zhang et al. 2007b), which may also induce the large scatter in the Type II sample. Finally, since many Type I GRBs only have upper limits on the optical luminosity, the reduced scatter that seems to be visible in Fig 7 is probably not real.

We also plot the effect of an unknown redshift. Here, we use GRB 060313 as an example, since it has a well-determined prompt emission spectrum and a well-observed afterglow too. We determine the isotropic bolometric energy release assuming the GRB actually lies at $z = 0.1, 0.3, 0.5, 0.7, 1.0, 1.3, 1.5, 1.7$, and 2.0, as well as the magnitude shift dR_C for these redshifts (ignoring the fact that UVOT detections in all bands imply $z \lesssim 1.3$, Roming et al. 2006), and then use the shifted light curve to determine the flux density at one day assuming $z = 1$. The results are shown as data points connected by a spline. They rise more rapidly than the slope of the correlations, implying that an unknown redshift will have a significant effect on the scatter and on the fit results if one were to add these additional GRBs.

4.3.2. The Optical Luminosity vs. the Host Galaxy Offset

Figure 8 shows the afterglow magnitude of Type I GRBs (the same data as in Fig. 7) plotted against the offset from their host galaxy. Once again, we differentiate between detections and upper limits and secure and insecure redshifts. If we concentrate on the secure redshifts only, a clear trend emerges, with larger offsets implying fainter magnitudes. This trend once again indicates the probable effect of the density of the circumburst medium on the kinetic energy conversion efficiency and thus the afterglow magnitude. For the cases with insecure redshift, the scatter is much larger, with GRB 051227 (faint afterglow centered on the host) and the high-redshift solution of GRB 060121 (extremely bright afterglow with a moderate host offset) being the strongest outliers.

Again, we use GRB 060313 to analyze the effect of an unknown redshift. The derived track is roughly perpendicular to the trend mentioned above, implying a strong dependency on redshift. The track of GRB 060313 crosses the trend at roughly $z \approx 0.6$. Interestingly enough, the $z = 1.7$ solution of GRB 060121 is quite close in both afterglow magnitude and host offset to GRB 060313 at a similar redshift, at first glance implying a similar track for GRB 060121 and a naive "prediction" of a redshift around $z \approx 0.6$. Independent of the validity of the trend as a rough redshift indicator, the track for GRB 060121 would be different, though, as the red afterglow would imply a strong extinction correction at such a low redshift (de Ugarte Postigo et al. 2006), which would correct the afterglow magnitude up again (no extinction correction has been assumed for GRB 060313).

4.3.3. The Bolometric Isotropic Energy vs. the Duration

Berger (2007c) researched a possible correlation between T_{90} and E_{iso}, and found tentative evidence for a correlation between the two parameters. With our larger sample, we repeat this analysis. We correct the T_{90} times for the redshift[10], and, in contrast to Berger (2007c), our isotropic energies are bolometric. In the case of GRBs which have an extended soft emission component (ESEC), we separate this total T_{90} from the duration of the initial pulse complex (IPC) only, which is shorter than 5 seconds in all cases. Fig. 9 shows the plotted data. Disregarding the T_{90} values which include an ESEC, a trend seems to be visible, both in the sample with secure redshifts only and in the complete sample, but the scatter is very large, and we caution that biases may be involved.

We once more use GRB 060313 to derive a redshift track. Again, this GRB is very suited for this analysis, as it was exceedingly bright and had the highest (lower limit) ratio of IPC to ESEC emission (Roming et al. 2006), therefore our naive T_{90} transformation with redshift is expected to be adequate. Similar to the effect of an unknown redshift on host galaxy offset (Fig. 8), the track is roughly vertical to the trend seen in Fig. 9 and thus redshift uncertainty may strongly contribute to scatter. In this case, GRB 060313 agrees with the values of other GRBs only for low redshifts $z \lesssim 0.5$. If a redshift $z \approx 1$ is confirmed spectroscopically, it will be a strong outlier in this plot, indicating the lack of a true correlation.

We also compared the T_{90} with the host galaxy offset. We find marginal evidence that Type I GRBs with an ESEC (i.e., large T_{90}) typically have a smaller host galaxy offset than GRBs that consist of an IPC only. This result was independently discovered by Troja et al. (2008), and we refer to this paper for a deeper analysis and discussion on why this may indicate two different progenitor types.

4.3.4. The Optical Luminosity as a Function of Redshift

In Fig. 10, we plot the absolute magnitude M_B of all Type I and Type II GRBs in our sample over the redshift of the GRBs. There is clearly a "zone of avoidance" in the lower right corner. If we plot the constant observer frame luminosity $C - 5log(D_L)/log(10)$ (with

[10]We caution that, in lieu of a complicated analysis of the prompt emission, we simply derive $T_{90}/(1+z)$. A more correct approach would need to involve the modeling of detector thresholds and a temporally resolved spectral analysis of the prompt emission to determine which parts would still be detectable at different redshifts. This is especially important for the ESEC component, which typically has both a very low peak flux as well as soft emission, and thus rapidly becomes undetectable with rising redshift.

the normalization constant $C = 1.5$ in this case), shown as a dashed line, it becomes clear that this effect is due to the optical detector threshold, in this case the limiting magnitude that the telescopes used for observations can reach. This is similar to the detector threshold bias in high energy observations (Butler et al. 2007). Another point, different from detector thresholds, is how much effort is (can be) actually invested into obtaining deep observations. GRB 050509B is a good example, being the first well-localized Type I GRB, it triggered an unprecedented observing campaign, yielding very deep early limits (Fig. 1). Another strong bias in the case of Type II GRB afterglows comes from the sample selection criteria, especially the need for a spectroscopic redshift, which favors afterglows that are bright in the observer frame (K06, Paper I). For Type I GRBs, this bias is reduced, as all redshifts have been derived from host galaxy spectroscopy, but here, the need for (at least) an X-ray afterglow detection to determine the host identification with sufficient significance yields a similar effect. An outlier of this threshold is GRB 051227 at an assumed redshift $z = 1$. This afterglow was only discovered due to very deep observations with 8m class telescopes (Malesani et al. 2005a,c; Berger et al. 2006b). In this case, the redshift assumption is almost irrelevant, as changing the redshift will move the data point more or less parallel to the threshold line. We illustrate this again with GRB 060313. Interestingly, the absolute magnitudes of several Type I GRB afterglows with uncertain redshifts, all of them bright high-fluence events, lie exactly on this line: GRB 061201 (which is quite similar to GRB 060313, App. A) at $z = 0.111$, GRB 070707 at $z = 0.5$, and the $z = 1.7$ solution of GRB 060121.

Another result from this plot pertains to the redshift-dependent luminosity bimodality of Type II GRB afterglows (K06, Liang & Zhang 2006; Nardini et al. 2006, 2008, Paper I). Clearly, with three exceptions (GRB 030329 at $z = 0.17$, GRB 071010A at $z = 0.99$ and GRB 991216 at $z = 1.02$), the afterglows at $z \leq 1.4$ are less luminous as a class than the afterglows at $z \geq 1.4$.

4.4. "Hybrid Indicator" GRBs in the Light of their Optical Afterglow Luminosities

In this chapter, we will discuss three events that are in our Type I GRB sample which are contested. They have "hybrid indicators", with some of the population indicators pointing to a Type I (merger population) origin and some pointing to a Type II (collapsar population) origin. Next to the indicators already discussed in § 2.1, we can now add the optical afterglow luminosity at one day after the GRB assuming $z = 1$, as we have shown that Type I GRB afterglows are typically a factor 100 fainter than Type II GRB afterglows.

4.4.1. GRB 060121

Donaghy et al. (2006) present a detailed analysis of the prompt emission properties of this GRB. They find $T_{90} = 1.60 \pm 0.07$ seconds in the energy range $85 - 400$ keV, close to the "borderline" but still within the classic BATSE short GRB definition. Furthermore, the spectral lag is negligible, and the prompt light curve shows the IPC + ESEC shape. The fluence is among the highest in the Type I sample, but much smaller than bright Type II GRBs (Paper I). The observed afterglow is extremely faint and very red. The host galaxy offset is larger than for a typical Type II GRB.

What makes this event extraordinary is the implied very high redshift (de Ugarte Postigo et al. 2006; Levan et al. 2006; Berger et al. 2006b). If the GRB really lies at $z \sim 4$, then the isotropic energy release is comparable to the more powerful Type II GRBs (Paper I), and the afterglow luminosity is typical for a Type II GRB too. Even if one assumes $z = 1.7$ (de Ugarte Postigo et al. 2006), the event is an outlier in comparison to the other Type I GRBs, and the additional problem of the high line-of-sight extinction that is needed (de Ugarte Postigo et al. 2006) emerges. A yet lower redshift (e.g., $z = 0.5$ which we assume for some other GRBs in the sample) eases the energy problem, but the extinction has to be increased even more, and the inferred low-luminosity of the host galaxy becomes an additional factor to consider. In any case, the afterglow light curve points to extreme collimation (de Ugarte Postigo et al. 2006, find $\theta_0 = 0.^{\circ}6$ for the $z = 4.6$ case from broadband modelling), which is hardly achievable within the context of compact object mergers (Aloy et al. 2005).

If this is a Type I GRB, it indicates that in rare cases the isotropic energy release is comparable to Type II GRBs, and the afterglow luminosity is not an indicator of the progenitor population. If this is a Type II GRB, then the problem emerges of how to explain the extremely short prompt emission, ~ 0.3 s at high energies in the rest frame assuming $z = 4.6$, in the framework of the collapsar model. Zhang et al. (2003) show that, under special conditions, the jet breakout from the massive star can produce a bright short emission spike, which is then followed by the lower-luminosity long GRB. This is exactly the IPC+ESEC light curve seen for GRB 060121 (but also for events like GRB 050724 which are clearly not associated with massive stars). But these authors also note that the initial bright spike should dominate only in flux, not in fluence, as is the case for GRB 060121. Note that the negligible spectral lag is not evidence against a GRB being Type II, as extremely luminous long GRBs can have negligible spectral lag (e.g., GRB 050717, Krimm et al. 2006). A host galaxy redshift might help to solve the affiliation of this enigmatic event, but the extremely faint host ($R_C \approx 26.5$, Levan et al. 2006; Berger et al. 2006b) may prevent such a measurement before the next generation of large optical telescopes.

4.4.2. GRB 060614

GRB 060614 is the much-discussed sample of a temporally very long GRB ($T_{90} = 102$s) that nonetheless seems to belong to the Type I GRB population, having negligible spectral lag while being subluminous at the same time (Gehrels et al. 2006; Mangano et al. 2007), a host galaxy with a small specific star-formation rate (Gal-Yam et al. 2006; Della Valle et al. 2006a), a large offset in terms of half-light radius and brightest pixel distribution (Gal-Yam et al. 2006) and a missing SN component down to $M_R \gtrsim -13.6$ (Fynbo et al. 2006; Gal-Yam et al. 2006; Della Valle et al. 2006a). The prompt emission light curve has been shown to be an extreme IPC+ESEC form, similar to other Type I GRBs but at higher luminosity (Zhang et al. 2007a). One difference to other Type I GRBs is that it does obey the Amati relation (Amati et al. 2007), although it clearly does not follow other luminosity indicators (Schaefer & Xiao 2006).

We find that in accordance with the relatively high isotropic energy release, the afterglow luminosity at late times is also quite high – for a Type I GRB. We thus do not contradict earlier interpretations. Still, the extreme light curve shows the need to develop merger models that are able to accommodate such long periods of sustained bright emission. Mergers involving white dwarfs may be a solution (King et al. 2007).

4.4.3. GRB 060505

With the discovery of significant spectral lag for this event (McBreen et al. 2008), this event has become of crucial importance. In light of all data on this GRB, one of two "gold indicators" of progenitor affiliation must be incorrect in at least some cases. Either not all merger population GRBs show negligible spectral lag, or not all collapsar population GRBs show a supernova component. Either way, this GRB breaks with the Type I and Type II classification proposed by Zhang (2006) and Zhang et al. (2007a).

In comparison to the extreme length of GRB 060614, the $T_{90} = 7.9$ s of GRB 060505 (McBreen et al. 2008) is still marginally in agreement with a long tail of the short GRB distribution (Donaghy et al. 2006). The fact that the host environment, a low-metallicity super starcluster in a spiral galaxy, strongly resembles the typical blue starburst host galaxies of Type II GRBs (Thöne et al. 2008) is also not a definitive argument against this being a Type I event (Ofek et al. 2007a), as by now the majority of Type I GRB host galaxies have been found to be actively starforming (Berger et al. 2006b)[11]. Also, the negligible offset from

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[11]We caution that the redshifts derived from host galaxy observations are strongly biased toward star-

the star-forming region is not a conclusive argument for a Type II event, as Belczynski et al. (2006) show that compact object mergers can occur within just a few million years after a starburst via a common envelope phase channel. On the other hand, the fact that the GRB does not obey the Amati relation (Amati et al. 2007) is also not a strong indication of this being a Type I event, as several clear collapsar events (GRB 980425, GRB 031203) are also not in accordance with the Amati relation. The one strong argument for this being a Type II GRB is the significant spectral lag, and the one strong argument for this being a Type I GRB is the deepest non-detection of a supernova in a GRB afterglow light curve ever.

From a theoretical standpoint, there is no compelling reason for Type I GRBs to have negligible spectral lag. Salmonson (2000) and Ioka & Nakamura (2001) interpret the lag-luminosity correlation (Norris et al. 2000) as a kinematic effect, dependent on the viewing angle from which we see the jet and on the Lorentz factor. One may now speculate that the jets of Type I GRBs have higher Lorentz factors, and thus smaller lags, as they propagate into a cleaner environment, since they do not have to penetrate a heavy stellar envelope and are thus less affected by baryon loading. A test of this hypothesis awaits the measurement of the Lorentz factors of Type I GRB jets, something that is non-trivial even for the much brighter afterglows of Type II GRBs (e.g., Molinari et al. 2007). Concerning a missing SN component, we have already pointed out that several authors have proposed the "fallback black hole" scenario which results in a GRB without an accompanying supernova (Fryer et al. 2006, 2007). Nomoto et al. (2007) and Tominaga et al. (2007) show that GRB-producing relativistic jets can be launched with negligible Ni^{56} production, leading to the absence of supernova emission. But it seems that such events must be either rare or usually very subluminous, thus evading detection.

From the afterglow luminosity perspective, in retrospect, we have discussed this GRB within the Type I sample, as it shows an intrinsically extremely faint afterglow that is as much an outlier in comparison to the Type II GRB afterglows as GRB 060121 is an outlier compared to the Type I GRB afterglows. If this truly is a Type II event, we are left with a uniquely subluminous GRB, one that is faint in the prompt emission, in the afterglow *and* in the supernova emission, the latter implying that only a small amount of energy is deposited in the subrelativistic ejecta too, in strong contrast to the other subluminous local universe events. Therefore, if the progenitor is of similar mass as a typical Type II GRB collapsar, most of the kinetic and rest mass energy of the collapsing core must fall rapidly without

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forming galaxies, as their emission lines are detectable at much higher significance than absorption lines in non-star-forming hosts. Furthermore, there are indications that offsets are larger in the case of massive elliptical hosts (such as for GRB 050509B and GRB 060502B, Gehrels et al. 2005; Bloom et al. 2007a), making the association with these galaxies less secure (cf. Troja et al. 2008).

significant emission through the event horizon of the central engine.

5. SUMMARY & CONCLUSIONS

We have compiled a complete set of optical/NIR photometry of *Swift*-era Type I GRB afterglows, both detections and upper limits, creating a total sample of 31 GRBs, considering events up to the end of November 2007. Using the methods of Zeh et al. (2006) and K06, and assuming reasonable values in cases where parameters like the redshift and the spectral slope are unknown, we analyzed the light curves and derived the luminosity distribution of the optical afterglows of Type I GRBs. Furthermore, we collected data on the energetics, and other prompt emission parameters, of the GRBs, as well as host galaxy offsets. With this sample, we are able, for the first time, to compare the parameter spaces of Type I GRBs to those of Type II GRBs from the sample of Paper I (both pre-*Swift* and *Swift* GRBs), both in terms of optical luminosity as well as in terms of energetics. To summarize, we come to the following results.

- Observationally, the optical afterglows of Type I GRBs are significantly fainter than those of Type II GRBs. Many Type I GRBs do not have any optical detections at all, and often these non-detections reach upper limits much deeper than the magnitudes of our (biased) Type II GRB afterglow sample at similar times. Type II GRBs not detected to similar depths are usually dark GRBs.

- The luminosity distribution of Type I GRB afterglows shows a larger scatter than for Type II GRBs, which have been found to cluster in luminosity space. The fact that many Type I GRBs have upper limits on their optical afterglows only implies that the luminosity distribution is even broader than we find. With few exceptions, the results for assumed redshifts agree with those for GRBs with redshifts we consider secure, implying that our assumptions were not too far off the mark. We find that the afterglows of Type I GRBs are, in the mean, five magnitudes fainter than those of Type II GRBs. This is further support that Type I and Type II GRBs have different progenitors, exploding in different environments.

- We find no evidence for the existence of radioactive-decay-driven supernova emission in the light curves of Type I GRB afterglows, confirming earlier studies, and adding several more examples of strong upper limits.

- We research the parameter space of Li & Paczyński mini-SNe, driven both by the decay of radioactive elements as well as neutrons, and strongly rule out the brightest emission models.

- Using our knowledge of the energetics and typical afterglow luminosities of Type I GRBs, we explore theoretically why their afterglows are even fainter than predicted by Panaitescu et al. (2001).

- In Paper I, we found a very tentative correlation, with a large degree of scatter, between the isotropic bolometric energy release and the afterglow luminosity at a fixed late time. The Type I GRB results extend this correlation to smaller energies and lower luminosities. We find a different normalization of the fit, which can be explained by a strong difference in the density of the external medium into which the jets propagate.

- Another trend that confirms expectations is found between the host galaxy offset and the afterglow luminosity. If confirmed by more data, it may be used as a rough redshift indicator.

- A trend between the duration and the isotropic energy release is not detected in a significant way.

- We discuss three anomalous GRBs, which have been assumed to be Type I GRBs, in the light of the results on their optical luminosities.

  1. GRB 060121 is found to resemble Type II GRBs much more than Type I GRBs, but would then have an extremely short prompt emission spike.
  2. GRB 060614, notwithstanding its extreme duration, is in good agreement with the upper end of the Type I GRB distribution in terms of energetics and afterglow luminosity, and thus seems to represent an extreme case of an Extended Soft Emission Component.
  3. GRB 060505 remains a puzzling object. The recent measurement of a significant spectral lag by McBreen et al. (2008) would place it with the Type II GRBs (in agreement with the environment), whereas the total lack of a supernova and the very low optical afterglow luminosity we derive are more akin to Type I GRBs. We pose the question if the existence of significant spectral lag truly is a surefire indication that a GRB is a Type II event.

One of the main results of Paper I was that the afterglows of pre-*Swift* and *Swift* Type II GRBs are, all in all, very similar to each other. Here, we clearly find that this is not the case for Type II and Type I GRB afterglows, the latter are much less luminous. The number of detected afterglows as well as the density of the follow-up observations is still too small to derive if the light curve evolution is also significantly different. More than a decade has passed since the afterglow era began, but for a long time, it was the Type II GRB afterglow

era only. The Type I GRB afterglow era is only three years old, and this study can only be a first exploration into a research area that is just now becoming accessible to us, thanks to an ever-evolving follow-up technology which allows us to be there faster, more precise and deeper all the time. And only a much larger sample will tell where exactly peculiar "hybrid indicator" GRBs are to be found in the ever-expanding zoo that is the GRB parameter space.

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A. DETAILS ON TYPE I GRBS

GRB 050509B. This was a very faint and exceedingly short single-spiked *Swift*-localized GRB, with $T_{90} = 0.04 \pm 0.004$ s, to which the satellite slewed immediately. *Swift* detected an extremely faint X-ray afterglow which was gone after the first orbit (Gehrels et al. 2005). The proximity of the X-ray afterglow to a bright cD elliptical galaxy, 2MASX J12361286+285858026 in the galaxy cluster NSC J123610+28590131, was quickly noted, and it was proposed that this GRB was a merger event occurring in the halo of this galaxy, which lies at $z = 0.2248 \pm 0.0002$ (e.g., Gehrels et al. 2005; Bloom et al. 2006; Castro-Tirado et al. 2005). Still, the error circle is quite large and contains many faint and probably more distant galaxies, so the association with the elliptical galaxy is not absolutely secure. Follow-up observations found no sign of supernova emission down to very deep limits, supporting the merger hypothesis (Hjorth et al. 2005a; Bersier et al. 2005). Upper limits are taken from Rykoff et al. (2005), Woźniak et al. (2005), Bloom et al. (2006), Cenko et al. (2005), Hjorth et al. (2005a), and Bersier et al. (2005), where we presume R-band observations for the last source. These upper limits are among the most constraining ever taken on a GRB afterglow.

GRB 050709. This GRB was localized by *HETE-2* (Villasenor et al. 2005) and was the very first Type I GRB for which an optical afterglow was discovered (Hjorth et al. 2005b; Fox et al. 2005b; Covino et al. 2006), it was also marginally detected in the NIR (Fox et al.

2005b). The subarcsecond localization was possible through the late detection of the X-ray afterglow with *Chandra*. The burst was localized to a star-forming dwarf galaxy at $z = 0.1606 \pm 0.0001$ (Fox et al. 2005b; Covino et al. 2006; Prochaska et al. 2006), immediately emphasizing the possibility of Type I GRBs to also come from galaxies with current star formation, just like Type Ia SNe. The burst itself has $T_{90} = 0.07 \pm 0.01$ s at high energies, was multispiked but had a low peak energy, and was followed by a bump of soft extended emission that has $T_{90} = 130 \pm 7$ s (Villasenor et al. 2005). Details on our construction of the afterglow light curve and SED, and the evidence for dust along the line of sight, can be found in Ferrero et al. (2007).

GRB 050724. This *Swift*-localized GRB featured more "firsts". It was similar to GRB 050709 in the sense that it consisted of a short, hard spike of 0.25 s duration, some further emission ($T_{90} = 3.0 \pm 1.0$ s Barthelmy et al. 2005a) and a bump of soft extended emission (total $T_{90} = 152.4 \pm 9.2$ s, Campana et al. 2006). The X-ray afterglow was bright and featured, for the first time, two late X-ray flares (Campana et al. 2006). Follow-up observations with *Chandra* showed that the afterglow was not strongly collimated (Grupe et al. 2006). GRB 050724 was the first Type I GRB with a clearly detected NIR afterglow and a radio afterglow (Berger et al. 2005b), and it was the first time that a GRB was securely associated with a galaxy that had no contemporaneous star formation (Barthelmy et al. 2005a; Berger et al. 2005b; Gorosabel et al. 2006), residing in a lone elliptical galaxy at $z = 0.2576 \pm 0.0004$ (Berger et al. 2005b; Prochaska et al. 2006). Afterglow data is taken from Berger et al. (2005b), and Malesani et al. (2007b).

GRB 050813. This was a faint event localized by *Swift*, which slewed immediately to the burst (Retter et al. 2005). The X-ray afterglow was extremely faint, similar to that of GRB 050509B (Morris et al. 2005). The burst had $T_{90} = 0.6 \pm 0.1$ s and another faint peak at 1.3 s, but no extended emission (Sato et al. 2005). Over time, the X-ray error circle has been revised and improved several times (see figure 1 of Ferrero et al. 2007). Observations of the error circle revealed a galaxy cluster at a redshift of $z \approx 0.72$ (Prochaska et al. 2006), which is believed to be associated with the GRB. We note that there is also photometric evidence for a background cluster (Berger 2006a). We use upper limits from Li (2005), Blustin et al. (2005a) and Ferrero et al. (2007).

GRB 050906. This was a very faint single-spiked GRB with $T_{90} = 0.128 \pm 0.016$ s localized by *Swift*, which slewed immediately to the burst, but did not detect any X-ray afterglow, leaving only the BAT error circle (Parsons et al. 2005a). Levan et al. (2007b) report deep

observations of the error circle, which includes, at its edge, the massive star-forming spiral galaxy IC 328 ($z = 0.031$). Furthermore, a galaxy cluster at $z = 0.43$ lies in the error circle. One possibility is that GRB 050906 is a SGR hyperflare from IC 328, but the softness of the spectrum speaks against this (Hurley et al., in preparation). Otherwise, the burst may be associated with the galaxy cluster, in which case it would energetically resemble GRB 050509B. A third possibility is a field galaxy at unknown redshift. In this work, we assume that this is a normal Type I GRB associated with the $z = 0.43$ cluster. Upper limits are taken from Fox et al. (2005a) and Levan et al. (2007b).

GRB 050911. This was a faint double-peaked burst followed by probably softer emission at 10 seconds after the trigger, it is $T_{90} = 16 \pm 2$ s. *Swift* was unable to slew to the burst immediately and no X-ray afterglow was detected to a deep limit in observations starting 4.6 hours after the trigger, indicating a faint and steeply decaying afterglow. While there were some doubts that this was a Type I GRB, the presence of soft emission bumps has come to be seen as a typical sign of this type of GRB. Furthermore, the spectral lag was negligible. Information on the *Swift* observations can be found in Page et al. (2006). The BAT error circle coincides with the galaxy cluster EDCC 493 at $z = 0.1646$. Berger et al. (2006a) find the significance of an association with GRB 050911 is 3.4σ, thus we use this redshift in this work. We take upper limits on an optical afterglow from Tristam et al. (2005), Berger et al. (2005a), Breeveld et al. (2005), and Page et al. (2006).

GRB 051105A. This was a very faint and extremely short GRB, $T_{90} = 0.028 \pm 0.004$ s (Cummings et al. 2005a). Although *Swift* immediately slewed, no X-ray afterglow was detected at all (Mineo et al. 2005). There are several faint and constant X-ray sources, one of them associated with a galaxy (Klose et al. 2005) which does not show optical variability and may be an X-ray selected quasar (Halpern et al. 2005). We assume $z = 0.5$. Upper limits are taken from Brown et al. (2005), Halpern et al. (2005), and Sharapov et al. (2005).

GRB 051210. This was a faint two-spiked GRB localized by *Swift*, which slewed immediately to the burst. The burst had $T_{90} = 1.27 \pm 0.05$ s and showed soft extended emission (La Parola et al. 2006). Within the XRT error circle, a host galaxy was discovered (Bloom et al. 2005a; Berger et al. 2006b), spectroscopy of this galaxy reveals neither emission nor absorption lines. Berger et al. (2006b) argue that this implies $z \geq 1.4$, we adopt $z = 1.4$. No optical afterglow was discovered, we take upper limits from Jelínek et al. (2005a), Berger & Boss (2005), Bloom et al. (2005a), Blustin et al. (2005b), and Berger et al. (2006b).

GRB 051211A. This event was localized by *HETE-2*, it was a multi-peaked burst with $T_{90} = 4.02 \pm 1.82$ s at high energies. The initial hard spike was detected by FREGATE and WXM, and the localization was derived from SXC which independently detected a soft extended bump. While T_{90} is high for a classical Type I burst, spectral analysis shows zero lag. *Swift* XRT follow-up observations started half a day after the GRB and revealed no X-ray afterglow, so the best position is the $80''$ SXC error circle. Within this error circle, Guidorzi et al. (2005) detected a candidate afterglow, but this is probably a star (Halpern & Mirabal 2006). We take upper limits from Guidorzi et al. (2005), Klotz et al. (2005), Jelínek et al. (2005b), and de Ugarte Postigo (2005). As no host galaxy or redshift is known, we assume $z = 0.5$.

GRB 051221A. This was an intense, multi-spiked burst localized by *Swift*, which slewed immediately to it (Parsons et al. 2005b). It was also detected by *Konus-Wind* (Golenetskii et al. 2005), *Suzaku-WAM* (Endo et al. 2005), *INTEGRAL SPI ACS*[12] and *RHESSI*. The burst has $T_{90} = 1.4 \pm 0.2$ s and shows no signs of extended emission (Cummings et al. 2005b). Bloom (2005) discovered the afterglow in the NIR, and it was soon confirmed in the optical. Soderberg et al. (2006a) present a multi-color host-corrected light curve, we use their data and that of Wren et al. (2005); for more details, see Ferrero et al. (2007). Spectroscopy shows that the GRB happened in a star-forming galaxy at $z = 0.5464$ (Soderberg et al. 2006a). The *Swift* and *Chandra* X-ray observations reveal what is probably a jet break at late times (between 2 and 9 days after the GRB), at a time when the afterglow is not detected anymore in the optical. The collimation-corrected energy is similar to that of the earlier Type I GRBs, indicating a standard energy reservoir and processes that lead to collimation similar to Type II GRBs (Burrows et al. 2006).

GRB 051227. This was a multi-peaked burst localized by *Swift*, which slewed immediately and flight-localized a bright X-ray afterglow (Barbier et al. 2005b). It was initially thought to be a Type II event, since it has $T_{90} = 8.0 \pm 0.2$ s (Hullinger et al. 2005), but spectral analysis showed negligible spectral lag, and together with a bump of soft emission starting several tens of seconds after the GRB, this indicated that GRB 051227 was a Type I event

[12]Light curves for triggered GRBs can be found at the following sites. *INTEGRAL SPI ACS*: http://isdc.unige.ch/cgi-bin/cgiwrap/~beck/ibas/spiacs/ibas_acs_web.cgi?month=200X-YY with X = 2, 3, etc. and YY = 01, 02, ... 12. *RHESSI*: http://grb.web.psi.ch/grb_list_200X.html with X = 2, 3, etc. *Suzaku WAM*: http://www.astro.isas.ac.jp/suzaku/HXD-WAM/WAM-GRB/grb/trig/grb_table.html for triggered events and http://www.astro.isas.ac.jp/suzaku/HXD-WAM/WAM-GRB/grb/untrig/grb_table.html for un-triggered events.

(Barthelmy et al. 2005b). Within the XRT error circle, an exceedingly faint afterglow was discovered (Malesani et al. 2005a). A nearby galaxy (Bloom et al. 2005b) was first thought to be the host galaxy, and was found to lie at $z = 0.714$ (Foley et al. 2005). But follow-up observations (Malesani et al. 2005c; Berger et al. 2006b) reveal a faint source directly underlying the afterglow position which does not fade in subsequent imaging and is thus the host galaxy. Together with those of GRB 060121, GRB 060313 and GRB 070714B, this is the faintest host galaxy so far found for a Type I GRB and suggests that it lies at an even higher redshift than the $z = 0.714$ galaxy. We thus adopt $z = 1$ for this GRB. Afterglow data is taken from Malesani et al. (2005b), Malesani et al. (2005c), and Berger et al. (2006b), and has been host-corrected. We find a very steep decay of $\alpha = 2.5 \pm 1.2$, which may be indicative of a highly collimated event observed after the jet break. The X-ray afterglow is not observed long enough to reveal a break at this time.

GRB 060121. This GRB was localized by *HETE-2*, it is a double-peaked burst with $T_{90} = 1.60 \pm 0.07$ s at high energies, which is followed by several hundred seconds of faint soft emission (Donaghy et al. 2006). It was also detected by *Konus-Wind* (Golenetskii et al. 2006a), *Suzaku WAM* and *RHESSI*. *Swift* did follow-up observations starting 3 hours after the GRB, and following the discovery of a bright X-ray afterglow (Mangano et al. 2006), the faint optical afterglow was discovered (Malesani et al. 2006a), finally leading to the discovery of an extremely faint host galaxy (Levan et al. 2006; Berger et al. 2006b). Analysis of the optical SED gives a best redshift solution of $z = 4.6$ (de Ugarte Postigo et al. 2006), which is supported by the host galaxy colors (Berger et al. 2006b), an alternate redshift solution is $z = 1.7$. There is evidence of an overdensity of Extremely Red Objects in the field, possibly a high redshift cluster (Levan et al. 2006; Berger et al. 2006b). At such a high redshift, the energetics, both of the prompt emission and the afterglow, are extreme in comparison to other Type I GRBs, being more typical for Type II GRBs (de Ugarte Postigo et al. 2006). This event is discussed in more detail in § 4.4. Details on the light curve construction are given in Ferrero et al. (2007).

GRB 060313. This event has been called "a new paradigm for short-hard bursts". It has the highest fluence, the highest observed peak energy and the second-highest hardness ratio (after GRB 060801) of all classical Type I GRBs observed by *Swift* (Roming et al. 2006). It is an intense, multi-spiked burst, $T_{90} = 0.7 \pm 0.1$ s, without any extended emission, the lower limit to the ratio of prompt to extended emission is also the largest in the *Swift* sample. It was also detected by *Konus-Wind* and *INTEGRAL SPI ACS*. The optical afterglow was discovered by the VLT (Levan & Hjorth 2006) after the XRT position was reported (Pagani & Burrows 2006), with the earliest detections coming from *Swift* UVOT

(Roming et al. 2006) and the Danish 1.54m (Thöne et al. 2006a). It remains roughly constant for several hours (Hjorth et al., in preparation) before fading rapidly. An extremely faint host galaxy is found at the afterglow position (Berger et al. 2006b, Hjorth et al., in preparation), making the afterglow of GRB 060313 also the brightest afterglow in relation to its host galaxy for a Type I GRB. Spectral analysis of the UVOT data gives $z \leq 1.1$ at 90% confidence (Roming et al. 2006), and the faintness of the host galaxy suggests a redshift near this limit. As with GRB 051227, we adopt $z = 1$. Afterglow data is taken from Thöne et al. (2006a), Cobb (2006), Nysewander et al. (2006), and Berger et al. (2006b), and we subtract the (small) host contribution. We do not use the UVOT data (Roming et al. 2006). Comparison with the early UVOT U and R_C data from the sources mentioned before indicates a very flat spectral slope.

GRB 060502B. This event was detected by *Swift* as a two-spiked GRB with $T_{90} = 0.09 \pm 0.02$ s, the satellite slewed immediately to it (Troja et al. 2006a; Sato et al. 2006a). No extended emission is detected, and observations did not reveal an optical afterglow. The revised XRT position (Troja et al. 2006b) lies close to a bright, early type galaxy which was first suggested as a possible host by Kann et al. (2006b), a position put forth in more detail by Bloom et al. (2007a), who find a redshift of $z = 0.287$ and note the similarity to GRB 050509B and GRB 050724. While we use this redshift in this work, we note that Berger et al. (2006b) propose a far fainter galaxy within the XRT error circle (for which no redshift is known) as an alternate possible host, implying a much higher redshift. We take upper limits for our analysis from Troja et al. (2006a), Poole & Troja (2006), Zhai et al. (2006), Price et al. (2006a), Rumyantsev et al. (2006), Berger et al. (2006b), and Bloom et al. (2007a).

GRB 060505. This burst was detected by *Swift* as it entered the SAA, and the image significance was too low to lead to a flight-generated position. Ground analysis derived a higher significance and the burst was reported as a weak event lasting $T_{90} = 4 \pm 1$ s (Palmer et al. 2006). *Suzaku WAM* and *RHESSI* also detected this GRB. Follow-up observations revealed a faint X-ray afterglow (Conciatore et al. 2006), and optical observations of the error circle lead to the discovery of an optical afterglow located in a spiral galaxy at $z = 0.089$ (Ofek et al. 2007a). Further observations revealed the absence of a supernova down to very deep limits (Thöne et al. 2006b; Fynbo et al. 2006; Ofek et al. 2007a), which posed the question if this was a Type II or a Type I GRB. The *Swift* high-energy data does not allow any conclusions due to its low quality (Schaefer & Xiao 2006) except that it does not follow the Amati relation (Amati et al. 2007), and the burst originated in a young, massive star-forming region as is typical for Type II GRBs (Ofek et al. 2007a; Thöne et al.

2008). But the optical data show that there must be very little dust along the line of sight, excluding high extinction as a reason for the faintness of the afterglow and the absence of the supernova (Ofek et al. 2007a; Thöne et al. 2008; Xu et al. 2007). This event is discussed in more detail in § 4.4. We take detections and upper limits from Ofek et al. (2007a) and Xu et al. (2007).

GRB 060614. This GRB, at first glance, seemed to be a classical high luminosity long GRB at moderate redshift (Schaefer & Xiao 2006). It was localized by *Swift* (Parsons et al. 2006), which slewed immediately to the burst and also discovered the optical afterglow. Due to its brightness, it was also detected by *Konus-Wind* (Golenetskii et al. 2006b) and *RHESSI*. Initial spectroscopy (Fugazza et al. 2006) revealed no lines, but a redshift of $z = 0.1254 \pm 0.0005$ was found several days later (Price et al. 2006b; Della Valle et al. 2006a) from host galaxy lines. Further observations revealed the absence of a supernova (Fynbo et al. 2006; Gal-Yam et al. 2006; Della Valle et al. 2006a). A chance superposition with the faint, slightly star-forming galaxy (Cobb et al. 2006b) was ruled out strongly (Gal-Yam et al. 2006; Gehrels et al. 2006), leading to the conclusion that this was a temporally clearly long GRB ($T_{90} = 102$ s) that was not associated with they typical death of a massive star (Fynbo et al. 2006; Gal-Yam et al. 2006; Della Valle et al. 2006a). The observed optical afterglow of GRB 060614 is much brighter than that of any other Type I GRB, and we are able to create a high quality SED stretching from the UV to the NIR, taking data from Fynbo et al. (2006), Gal-Yam et al. (2006), Della Valle et al. (2006a), Cobb et al. (2006b), Mangano et al. (2007), and Yost et al. (2007). Our SED results are in agreement with Della Valle et al. (2006a), the amount of dust along the line of sight is low and within the typical range found by K06 and Paper I for Type II GRBs. Still, Mangano et al. (2007) find, for SMC dust, an even lower value than we do, $A_V = 0.05 \pm 0.02$. As the 2175 Å feature is covered by the *Swift* UVOT filters, we are able to derive a clear preference for SMC dust, as this feature is not visible. This is the first low-redshift GRB for which this has been possible in our analysis (cf. K06). For SMC dust, we find $\beta = 0.41 \pm 0.09$, $A_V = 0.28 \pm 0.07$ and a very good fit ($\chi^2_{d.o.f.} = 0.72$). As Della Valle et al. (2006a), we find that the late afterglow (after the rising phase, Gal-Yam et al. 2006) can be fit with a broken power law. Using the precise host magnitude measurements from Della Valle et al. (2006a), we subtract the host galaxy from these data points and merge them with other, host-corrected sets. We derive the following light curve parameters: $m_k = 20.32 \pm 0.05$ mag, $\alpha_1 = 1.05 \pm 0.04$, $\alpha_2 = 2.42 \pm 0.05$, $t_b = 1.30 \pm 0.03$ days, and $n = 10$ was fixed (see Zeh et al. 2006, for a description of these parameters). Again, this is the only Type I GRB afterglow where such an analysis could be performed. This event is discussed in more detail in § 4.4.

GRB 060801. This was a double-spiked burst (with a possible faint third peak) localized by *Swift*, which slewed to the burst immediately (Racusin et al. 2006a). It was also detected by *Suzaku WAM*. No extended emission was detected, $T_{90} = 0.5 \pm 0.1$ s, and the burst is one of the hardest *Swift* has ever detected (Sato et al. 2006b; Hjorth et al. 2006, their Figure 1). Follow-up revealed no optical afterglow (Brown & Racusin 2006; Duscha et al. 2006; Piranomonte et al. 2006b), but within the revised XRT error circle (Butler 2006) only a single galaxy was found (Castro-Tirado et al. 2006), lying at a redshift of $z = 1.1304$ (Berger et al. 2006b), making this the most distant Type I GRB with a secure redshift.

GRB 061006. This event was initially detected by *Swift* via a 64-second image trigger. IPN observations revealed this to be a bright Type I GRB with double-spiked emission lasting 0.5 seconds and occurring 22 seconds before the beginning of the *Swift* trigger, which *Swift* did not trigger on due to a preplanned slew (Hurley et al. 2006). *Swift* triggered on the extended emission of the GRB, $T_{90} = 130 \pm 10$ s, then slewed immediately. The *Swift* observations are detailed in Schady et al. (2006b). Initial observations (Schady et al. 2006a; Pandey & Schady 2006; Mundell et al. 2006) resulted in upper limits only, but VLT observations (Malesani et al. 2006b) found a faint source that was subsequently found to fade, revealing the host galaxy (Malesani et al. 2006c; Berger et al. 2006b). Berger et al. (2006b) report a redshift of $z = 0.4377 \pm 0.0002$ from several emission lines which indicate that this galaxy has moderate star-formation. Relevant data have been taken from the sources aforementioned, with the afterglow data point being host-subtracted.

GRB 061201. This was a bright, multi-peaked GRB with $T_{90} = 0.8 \pm 0.1$ s localized by *Swift* and also observed by *Konus-Wind* (Golenetskii et al. 2006d). *Swift* slewed immediately to the burst which showed no sign of extended emission. The optical afterglow was discovered by UVOT and was seen to remain roughly constant for a long time, similar to the one of of GRB 060313. *Swift* and VLT observations can be found in Stratta et al. (2007). While it has been suggested that the GRB may be associated with the galaxy cluster Abell 995 (Bloom 2006) at a redshift of $z = 0.0865$ (Berger 2007a), the projected distance is very high. A more likely association is a star-forming galaxy first noted by D'Avanzo et al. (2006a) lying at a redshift of $z = 0.111$ (Berger 2006b; Stratta et al. 2007), at a distance of 34 kpc in projection. We use this redshift in this work but note the similarity of this GRB to GRB 060313, which probably lies at $z \approx 1$. Stratta et al. (2007) find no host galaxy down to $R > 25.9$; the host galaxy of GRB 060313 is even fainter. Also, similar to that GRB, GRB 061201 is well detected in the *Swift* UVOT UVW2 filter, and no sign of a Lyman dropout is seen, indicating $z \lesssim 1.3$ (the latter is of course no argument against the $z = 0.111$ association). Relevant data on this GRB, detections and late upper limits, have been taken

from Marshall et al. (2006), Holland & Marshall (2006b), and Stratta et al. (2007), where we use the observation times detailed in Holland & Marshall (2006b) to derive logarithmic mean times for the UVOT observations. We note that the afterglow of GRB 061201 is one of the faintest ever detected at early times and, assuming $z = 0.111$ to be correct, is at early times the intrinsically faintest afterglow ever observed.

GRB 061210. This was a very bright GRB consisting of triple-peaked emission lasting about 60 msec but followed by a long tail of soft emission, $T_{90} = 85 \pm 5$ s. It was localized by *Swift* (Cannizzo et al. 2006) and also detected by *Suzaku-WAM* (Urata et al. 2006). *Swift* was unable to slew due to moon constraint. XRT observations that began 2.42 days after the GRB revealed two uncatalogued sources, one which was found to fade and was thus identified to be the X-ray afterglow (Godet et al. 2006; Racusin et al. 2006b), indicating this was a very bright X-ray afterglow for a Type I GRB. While there are several sources within or near the error circle, the most likely host galaxy is a star-forming galaxy at $z = 0.4095 \pm 0.0001$ (Berger et al. 2006b). Relevant data on this GRB, all upper limits, are taken from Mirabal & Halpern (2006), Cenko et al. (2006b), and Melandri et al. (2006).

GRB 061217. This was a faint single-spiked GRB with $T_{90} = 0.212 \pm 0.041$ s localized by *Swift*. *Swift* slewed immediately to the burst which showed no sign of extended emission. The X-ray afterglow was very faint and initially wrongly localized. Details on the *Swift* observations can be found in Ziaeepour et al. (2007a). Within the XRT error circle, a star-forming galaxy at redshift $z = 0.8270$ is found (Berger et al. 2006b). Relevant data on this GRB, all upper limits, are taken from Schaefer (2006), Jelínek et al. (2006), D'Avanzo et al. (2006b), and Klotz et al. (2006).

GRB 070209. This was a faint single-spiked GRB with $T_{90} = 0.1 \pm 0.02$ s and no extended emission. It was detected by *Swift*, which slewed to it immediately, but no fading X-ray source was detected at all. *Swift* observations are detailed in Sato et al. (2007b). One constant X-ray source outside the BAT error circle is associated with an emission-line galaxy at $z = 0.314$ (Berger & Fox 2007), possibly an AGN. We assume $z = 0.5$. Relevant data on this GRB, all upper limits, are taken from Sato et al. (2007a) and Johnson et al. (2007), the latter being the only ground-based follow-up reported. As there are only early and quite shallow upper limits reported, no significant magnitude limit can be derived, so this burst is not further included in the results.

GRB 070406. This was a faint double-spiked GRB with $T_{90} = 0.7 \pm 0.2$ s detected by *Swift*. The image significance was too low for a flight localization, and the ground analysis position was reported 19 hours after the GRB. *Swift* ToO observations over the following 9 days revealed two faint X-ray sources, but both of them were found to be constant. One of these was associated with a bright blue galaxy visible in the SDSS data release (Cool et al. 2007), found by Kann (2007), who proposed it as a host galaxy but also noted the colors and that it might be an AGN. The latter interpretation was confirmed spectroscopically by Berger et al. (2007), who found it to be a quasar at $z = 0.703$. The second X-ray source is possibly also associated with an AGN (Berger 2007b). No X-ray or optical afterglow was found, we assume $z = 0.5$. The *Swift* observations are reported in McBreen et al. (2007). We take upper limits from Zheng et al. (2007), Malesani et al. (2007a), McBreen et al. (2007), and Bloom et al. (2007b). Assuming $z = 0.5$, these measurements span only a small time-span when shifted to $z = 1$, 1.1 to 1.6 days. The deepest and last upper limit is $R_C > 27$, we thus assume $R_C > 26$ at one day for any reasonable afterglow evolution.

GRB 070429B. This was a faint triple-spiked GRB with $T_{90} = 0.5 \pm 0.1$ s detected by *Swift*. The satellite slew was delayed by 165 seconds due to Earth-limb constraint. After slewing, a faint X-ray afterglow was detected in ground analysis. The *Swift* observations are reported in Markwardt et al. (2007b). Deep observations of the error circle revealed two faint galaxies of which one is probably the host (Cucchiara et al. 2007a; Antonelli et al. 2007). For the brighter galaxy, Perley et al. (2007e) reported a redshift $z = 0.904$, which is confirmed by Cenko et al. (2008). Reanalysis of the Swift UVOT data revealed a rising and then rapidly fading faint afterglow very close to the position of this galaxy Holland et al. (2007), making this another secure association. We take detections from Holland et al. (2007) and upper limits from Schaefer et al. (2007), Markwardt et al. (2007a), Antonelli et al. (2007), Perley et al. (2007e), and Holland et al. (2007).

GRB 070707. This GRB was detected by INTEGRAL and was first taken to be a temporally long event (Beckmann et al. 2007), but was shortly afterward announced to be a Type I GRB of 1.1 seconds length, the first of its kind to be rapidly and accurately localized by INTEGRAL (Götz et al. 2007). The moderately bright, multi-spiked event was also detected by Konus-Wind (Golenetskii et al. 2007b). *Swift* follow-up observations revealed an X-ray source that was subsequently seen to fade (Parsons et al. 2007), confirming it as the X-ray afterglow. Optical observations with the VLT (D'Avanzo et al. 2007a) revealed a single optical source in the X-ray error circle (Piranomonte et al. 2007), which was seen to fade, confirming it to be the optical afterglow (D'Avanzo et al. 2007b). It is unclear how much the host contributes at late times. No redshift is known, we assume $z = 0.5$. We take

upper limits from Parsons et al. (2007) and detections from D'Avanzo et al. (2007a), and D'Avanzo et al. (2007b).

GRB 070714B. This was a very bright multi-spiked event lasting about three seconds which was followed by soft extended emission which lasted to probably 100 seconds. *Swift* slewed immediately to the GRB and a bright X-ray afterglow was localized in flight. The *Swift* observations are presented in (Racusin et al. 2007). The GRB was not detected in spectral mode by *Konus-Wind* (V. Pal'shin, priv. comm.), but a joint *Swift* + *Suzaku-WAM* spectral analysis yielded a hard spectrum and a high peak energy (Ohno et al. 2007). An optical afterglow was discovered just 10 minutes after the GRB by the Liverpool Telescope (Melandri 2007), and was confirmed a day later by the WHT (Levan et al. 2007a). Host galaxy observations reveal a redshift $z = 0.92$ (Graham et al. 2007, 2008), confirmed by Cenko et al. (2008). Late observations (Perley et al. 2007a) show the source remains point-like at $R \approx 25.5$, and we note the similarity to GRB 051227 and GRB 060313, adding weight to the argument that these two GRBs lie at $z \approx 1$. We take upper limits from Racusin et al. (2007) and detections from Levan et al. (2007a), Covino et al. (2007a), Perley et al. (2007a), and Landsman et al. (2007).

GRB 070724. This was faint single-spiked GRB with $T_{90} = 0.4 \pm 0.04$ s localized by *Swift*, which slewed to it immediately, flight-localizing the X-ray afterglow. While no extended emission was seen, *Swift* detected two X-ray flares in the first 100 seconds, the first one rather bright, indicating that the GRB had extended emission, but it lay beneath the BAT detection threshold. The *Swift* observations are detailed in Ziaeepour et al. (2007b). A comparison with the DSS lead to the discovery of what seemed to be a blue host galaxy (Bloom 2007; Bloom & Butler 2007). Spectroscopy of the of the object confirmed it to be a star-forming galaxy at $z = 0.457$ (Cucchiara et al. 2007b; Covino et al. 2007b), and it is associated with the GRB at high probability. Deep imaging and image subtraction did not reveal an optical afterglow. We note that our analysis of the BAT data reveals this to be a quite soft event with an observed peak energy of just 41 keV and a photon index of $\Gamma = -2.2$, making this the first example of a "short/soft GRB". We take upper limits from Ziaeepour et al. (2007b), Cenko et al. (2007), Covino et al. (2007b), and D'Avanzo & Covino (2007).

GRB 070729. This was faint triple-spiked GRB with $T_{90} = 0.9 \pm 0.1$ s localized by *Swift*, which slewed to it immediately. The X-ray afterglow was faint and not flight-localized, similar to GRB 050509B and GRB 050813. The *Swift* observations are detailed in Guidorzi et al. (2007a). The GRB was also detected by the Konus-A experiment on Cosmos-2421 (Golenetskii et al.

2007c). Magellan observations revealed an extended K-band source within the XRT error circle, presumably the host galaxy (Berger & Kaplan 2007). The galaxy was found to be red (Berger & Murphy 2007). No redshift is known, we assume $z = 0.5$. Upper limits are taken from Guidorzi et al. (2007a) and Berger & Kaplan (2007).

GRB 070809. This was a faint triple-spiked GRB with $T_{90} = 1.3 \pm 0.1$ s localized by *Swift*, which slewed to it immediately. While not flight-localized, it had a moderately bright X-ray afterglow. The burst was relatively soft, which, combined with the relatively long duration, puts this burst in the realm intermediate between the clusters of Type I and Type II GRBs in the T_{90}-hardness diagram. Further analysis places this GRB clearly into the Type I category (Barthelmy et al. 2007). The *Swift* observations are detailed in Marshall et al. (2007a). Keck observations revealed a faint source with $R \approx 24$ at the edge of the XRT error circle (Perley et al. 2007b), which was found to have decayed significantly a day later, implying it to be the afterglow (Perley et al. 2007d). The afterglow is extremely red. No redshift is known, the spectrum of a nearby galaxy that may be an edge-on spiral showed no lines (Perley et al. 2007d). We assume $z = 0.5$. We take upper limits from Rykoff et al. (2007a) and Marshall et al. (2007a), and detections from Perley et al. (2007d).

GRB 070810B. This was faint FRED GRB with $T_{90} = 0.08 \pm 0.01$ s localized by *Swift*, which slewed to it immediately. No conclusive X-ray afterglow was detected. Deep XRT observations revealed several very faint X-ray sources. So far, none of these X-ray sources have been shown to fade. The Swift observations are detailed in Marshall et al. (2007b). Deep Keck observations linked one of the X-ray sources to a possibly interacting small cluster of galaxies, of which two seem to be strongly star-forming. The cluster lies at $z = 0.49$ (Thöne et al. 2007), we adopt this redshift. Furthermore, there is a large and nearby ($z = 0.0385$) early type galaxy (LEDA 1354367) in the BAT error circle (Marshall et al. 2007b; Thöne et al. 2007), but an association with this galaxy is unlikely due to the faintness of the GRB. A possible afterglow was reported in the $z = 0.49$ cluster (Rumyantsev et al. 2007) but it was found to not be fading (Kocevski et al. 2007). Upper limits are taken from Marshall et al. (2007b), Xin et al. (2007), Guidorzi et al. (2007b), Rumyantsev et al. (2007) and Kocevski et al. (2007).

GRB 071112B This was a faint double-peaked, very hard GRB with $T_{90} = 0.30 \pm 0.05$ s localized by *Swift*. The satellite only started observing the burst after an hour due to Earth Limb constraint, and no X-ray afterglow was detected. The *Swift* observations are detailed in Perri et al. (2007). The BAT error circle was observed by several large telescopes, but

no variable sources were found via image subtraction. We assume $z = 0.5$. Upper limits are taken from Rykoff et al. (2007b), Perri et al. (2007), Kocevski & Bloom (2007), and Wiersema et al. (2007).

Type I (and other short) GRBs not in the sample. The following Type I GRBs are not in the sample: GRBs 050112, 060303, 060425, 060427B and 060429 were all localized by the IPN to large error boxes only. GRBs 050202 (Tueller et al. 2005), 051114 (Cummings et al. 2005) and 070923 (Stroh et al. 2007) were localized by *Swift* BAT, but not followed up by optical observations, being very near the Sun (GRBs 050202 and 070923) or not reported until later in ground analysis (GRB 051114). GRBs 051103 and 070201 are thought to be extragalactic SGR hyperflares (Ofek et al. 2006; Frederiks et al. 2007; Perley & Bloom 2007; Golenetskii et al. 2007a; Hurley et al. 2007; Abbott et al. 2007; Ofek et al. 2007b), while the short but soft GRB 050925 is thought to be a small flare from an otherwise unknown Galactic SGR (Holland et al. 2005; Markwardt et al. 2005). Finally, the short INTEGRAL GRB 071017 is probably associated with a known Galactic X-ray source (Mereghetti et al. 2007; Evans et al. 2007).

B. CONSTRAINTS ON EXTRA LIGHT IN TYPE I GRB AFTERGLOWS: METHODS

SN1998bw light The procedure for calculating and redshifting a SN 1998bw component is explained in detail in Zeh et al. (2004).

The mini-SN model and the macronova model Following LP98ab we assumed the ejecta consists of a variety of nuclei with a very broad range of decay times. This leads to their power-law decay model. The equations given in LP98ab provide the bolometric luminosity, $L_{\rm bol}$, and the time-dependent effective temperature, $T_{\rm eff}$, of a mini-SN assuming black body radiation. We are interested in the R-band luminosity, L_R, which we write as $L_R(t) = y(t)\, L_{\rm bol}(t)$. Hence,

$$y(t) = \frac{\int_{\lambda_1}^{\lambda_2} \; S_R(\lambda) \; F_\lambda^{\rm bb}(T_{\rm eff}(t'), \lambda'; z) \; d\lambda}{\int_0^\infty \; F_\lambda^{\rm bb}(T_{\rm eff}(t'), \lambda'; z) \; d\lambda}\,, \tag{B1}$$

where $S_R(\lambda)$ is the filter response function in the R band, $F_\lambda^{\rm bb}$ is the Planck function, $t = t_{\rm obs}, t' = t_{\rm host} = t/(1+z)$, $\lambda' = \lambda/(1+z)$, and z is the redshift. The radius R of the non-relativistically expanding supernova is $R(t') = R_0 + vt'$, where v is the velocity of the ejecta which is assumed to be independent of time; R_0 is negligible. The effective temperature of

the supernova at the time t in the observer frame, needed to calculate $y(t)$, follows from $L_{\rm bol}(t)$.

The above formalism assumes (following LP98ab, and K05 as well) that the spherical ejecta is optically thick, so that its radiation can be described by a black body. This assumption holds up to a critical time, t_c (LP98ab, their Eq. 7), when the ejecta becomes optically thin:

$$t_c = 1.13 \text{ day } \left(\frac{M_{\rm ej}}{0.01}\right)^{1/2} \left(\frac{c}{3v}\right) \left(\frac{\kappa}{\kappa_e}\right)^{1/2} . \tag{B2}$$

Here $M_{\rm ej}$ is the ejected mass in units of solar masses, κ is the opacity of a gas, and the index e stands for electron scattering. While at $t > t_c$ the time evolution of the bolometric luminosity of the ejecta is approximately calculable (LP98ab), the fraction of luminosity that goes into the optical bands cannot be calculated anymore adopting a black body. Therefore, for $t \geq t_c$ our results are less reliable.

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Table 1. Properties of the Type I GRB Sample

GRB	Redshift z	T_{90} (s)[a] (IPC)	Fluence (10^{-7} erg cm^{-2})	Band (keV) (Satellite)[l]	$E_{iso,bol}$ (10^{50} erg)	$E_{p,rest}$ (keV)	Photon Index Γ[b]	Spikes in IPC	ESEC (Bump)	T_{90} (s)[c] (total)	Afterglow X/O/R?	Host offset (kpc)
050509B	0.2248 ± 0.0002	0.04 ± 0.004	0.2 ± 0.09	$15-350$ (S)	$48.38^{+0.45}_{-0.23}$	$100.4^{+748.4}_{-98.0}$	-1.7 ± 0.7	1	N	···	Y/N/N	71.1 ± 12.2
050709	0.1606 ± 0.0001	0.07 ± 0.01	14.93 ± 1.81	$2-400$ (H)	$49.93^{+0.05}_{-0.06}$	$100.4^{+18.6}_{-12.8}$	$-0.82^{-0.13}_{+0.14}$	≈ 3	Y	130 ± 7[d]	Y/Y/N	3.78 ± 0.03
050724	0.2576 ± 0.0004	3.0 ± 1.0[e]	15 ± 2	$15-350$ (S)	$50.38^{+0.38}_{-0.02}$	$138.4^{+503.3}_{-56.6}$	-1.6 ± 0.2[f]	1[g]	Y	152.4 ± 9.2	Y/Y/Y	2.57 ± 0.08
050813	≈ 0.72	0.6 ± 0.1	$1.0^{+0.3}_{-0.6}$	$15-350$ (S)	$50.18^{+0.43}_{-0.33}$	$361.2^{+1221}_{-223.6}$	-1.2 ± 0.5	1[h]	N	···	Y/N?/N	···
050906	0.43?	0.128 ± 0.016	$0.6^{+0.4}_{-0.3}$	$15-350$ (S)	$49.49^{+0.42}_{-0.59}$	$517.4^{+2282}_{-492.1}$	$-0.94^{-0.1.05}_{+0.99}$	1	N	···	N/N/N	···
050911	0.1646?	≈ 1.5	$4.4^{+0.9}_{-1.3}$	$15-350$ (S)	$49.43^{+0.39}_{-0.10}$	$63.9^{+419.9}_{-60.9}$	$-1.83^{-0.33}_{+0.36}$	2	Y	16 ± 2	N/N/N	···
051105A	···	0.028 ± 0.004	0.5 ± 0.2	$15-350$ (S)	$49.68^{+0.34}_{-0.39}$[i]	$450.6^{+1036}_{-327.6}$[i]	$-1.30^{-0.42}_{+0.43}$	1	N	···	N/N/N	···
051210	≥ 1.4	1.27 ± 0.05	$2.2^{+0.5}_{-0.8}$	$15-350$ (S)	$51.41^{+0.39}_{-0.48}$	$721.0^{+2104.9}_{-557.8}$	$-1.00^{-0.33}_{+0.31}$	2	Y	≈ 40	Y/N/N	43.0 ± 13.7
051211A	···	4.02 ± 1.82	8.0 ± 1.29	$2-400$ (H)	$50.70^{+0.16}_{-0.21}$[i]	$187.5^{+44.0}_{-36.2}$[i]	$-0.12^{-0.54}_{+0.21}$	≈ 4	Y	≈ 40	N/N/N	···
051221A	0.5464	1.4 ± 0.2	32^{+1}_{-17}	$20-2000$ (K)	$51.41^{+0.02}_{-0.33}$	$621.7^{+143.8}_{-111.3}$	$-1.08^{-0.13}_{+0.14}$	8	N	···	Y/Y/Y	0.76 ± 0.25
051227	···	8.0 ± 0.2	8.0 ± 1.0	$15-350$ (S)	$51.44^{+0.37}_{-0.20}$[j]	$270.0^{+1167.1}_{-128.2}$[j]	-1.09 ± 0.23	≈ 3	Y	≈ 100	Y/Y/N	0.40 ± 0.16[j]
060121	4.6	1.60 ± 0.07	47.7 ± 2.8	$2-400$ (H)	53.34 ± 0.05	$627.2^{+79.5}_{-68.9}$	$-0.78^{-0.12}_{+0.11}$	3	Y	≈ 120	Y/Y/N	2.00 ± 0.67
060121	1.7				52.61 ± 0.06	$302.4^{+38.3}_{-33.2}$						2.57 ± 0.86
060313	···	0.7 ± 0.1	129^{+15}_{-31}	$15-3000$ $(S{+}K)$	$52.54^{+0.05}_{-0.12}$[j]	1894^{+448}_{-346}[j]	$-0.61^{-0.09}_{+0.11}$	> 20	N	···	Y/Y/N	3.22 ± 0.80[j]
060502B	0.287?	0.09 ± 0.02	$1.2^{+0.2}_{-0.6}$	$15-350$ (S)	$49.48^{+0.43}_{-0.48}$	$437.6^{+926.6}_{-244.5}$	-1.0 ± 0.2	2	N	···	Y/N/N	71.0 ± 15.9
060505	0.0889	4 ± 1	6.2 ± 1.1	$15-150$ (S)	$49.40^{+0.23}_{-0.20}$	$243.0^{+326.3}_{-139.3}$	-1.3 ± 0.3	1	N	···	Y/Y/N	7.06 ± 0.33
060614	0.1254 ± 0.0005	≈ 5	409^{+18}_{-34}	$20-2000$ (K)	$51.40^{+0.05}_{-0.04}$	$438.9^{+922.8}_{-281.4}$	-1.90 ± 0.04	6[k]	Y	102 ± 5	Y/Y/N	1.1[illegible] $\pm$ 0.22
060801	1.1304 ± 0.0001	0.5 ± 0.1	$3.4^{+0.7}_{-2.3}$	$15-350$ (S)	$51.39^{+0.40}_{-0.50}$	$1424^{+2185}_{-883.7}$	$-0.43^{-0.30}_{+0.27}$	2	N	···	Y/N/N	17.2 ± 12.6
061006	0.4377 ± 0.0002	≈ 0.5	$35.7^{+3.1}_{-19.2}$	$20-2000$ (K)	$51.24^{+0.04}_{-0.34}$	$954.6^{+326.4}_{-207.0}$	$-0.62^{-0.18}_{+0.21}$	2	Y	130 ± 10	Y/Y/N	7.70 ± 2.96
061201	0.111?	0.8 ± 0.1	$53.3^{+7.0}_{-44.4}$	$20-3000$ (K)	$50.15^{+0.06}_{-0.78}$	$969.9^{+508.8}_{-315.5}$	$-0.36^{-0.40}_{+0.65}$	5	N	···	Y/Y/N	34.0 ± 2.0
061210	0.4095 ± 0.0001	≈ 0.06	$20.2^{+3.5}_{-3.3}$	$100-1000$ (Sz)	$51.06^{+0.14}_{-0.10}$	$761.1^{+1071}_{-436.9}$	-0.8 ± 0.1	3	Y	85 ± 5	Y/N/N	10.9 ± 9.9
061217	0.8720 ± 0.0001	0.212 ± 0.041	$1.2^{+0.3}_{-0.4}$	$15-350$ (S)	$50.48^{+0.37}_{-0.48}$	730.8^{+1480}_{-475}	-0.96 ± 0.28	1	N	···	Y/N/N	58.2 ± 29.5
070209	···	0.10 ± 0.02	$0.7^{+0.2}_{-0.3}$	$15-350$ (S)	$49.73^{+0.38}_{-0.39}$[i]	$498.0^{+875.0}_{-341.3}$[i]	-1.02 ± 0.33	1	N	···	N/N/N	···
070406	···	0.7 ± 0.2	0.45 ± 0.10	$15-150$ (S)	$50.32^{+0.70}_{-1.29}$[i]	1263^{+5072}_{-1011}[i]	-0.9 ± 0.4	2	N	···	N/N/N	···
070429B	0.9023 ± 0.0003	0.5 ± 0.1	0.6 ± 0.2	$15-350$ (S)	$50.13^{+0.42}_{-0.20}$	$232.2^{+1414.6}_{-130.8}$[i]	$-1.53^{-0.38}_{+0.40}$	3	N	···	Y/Y/N	8.27 ± 5.24
070707	···	≈ 1.1	$14.1^{+1.6}_{-10.7}$	$20-2000$ (K)	$50.95^{+0.05}_{-0.62}$[i]	$640.5^{+561.0}_{-216.0}$[i]	$-0.57^{-0.43}_{+0.59}$	≈ 12	N	···	Y/Y/N	···
070714B	0.9224 ± 0.0001	≈ 3	37^{+13}_{-6}	$15-2000$ $(S{+}Sz)$	$51.99^{+0.15}_{-0.10}$	$2150^{+1498}_{-729.6}$	-0.86 ± 0.10	> 4	Y	≈ 100	Y/Y/N	12.7 ± 5.0
070724	0.457	0.4 ± 0.04	$0.44^{+0.11}_{-0.20}$	$15-350$ (S)	$49.39^{+0.36}_{-0.15}$	$59.2^{+147.5}_{-54.2}$	$-2.18^{-0.24}_{+0.26}$	1	N	···	Y/N/N	4.38 ± 12.3[n]
070729	···	0.9 ± 0.1	$5.59^{+0.05}_{-4.38}$	$20-1000$ (KA)	$50.62^{+0.16}_{-0.68}$[i]	$700.5^{+1272}_{-292.5}$[i]	$-1.08^{-0.28}_{+0.36}$	3	N	···	Y/N/N	71.5 ± 15.2[i]
070809	···	1.3 ± 0.1	$1.35^{+0.21}_{-0.60}$	$15-350$ (S)	$49.86^{+0.33}_{-0.11}$[i]	$122.8^{+387.2}_{-48.6}$[i]	-1.58 ± 0.23	3	N	···	Y/N/N	···
070810B	0.49?	0.08 ± 0.01	$0.70^{+0.37}_{-0.43}$	$15-350$ (S)	$49.71^{+0.43}_{-0.52}$	$494.7^{+1372}_{-385.8}$	$-1.01^{-0.73}_{+0.64}$	1	N	···	N/N/N	···
071112B	···	0.30 ± 0.05	$1.81^{+0.60}_{-0.92}$	$15-350$ (S)	$50.24^{+0.34}_{-0.51}$[i]	$672.3^{+1271}_{-441.3}$[i]	$-0.83^{-0.50}_{+0.44}$	2	N	···	N/N/N	···

Note. — References for z and T_{90} can be found in § A. Further references for energetics (Fluence, Band, E_p, Photon Index): GRB 050509B: Butler et al. (2007); GRB 050709: Villasenor et al. (2005); GRB 050724: Barthelmy et al. (2005a); Campana et al. (2006); Butler et al. (2007); GRB 050813: Sato et al. (2005); Butler et al. (2007); GRB 050906: Parsons et al. (2005a); Butler et al. (2007), this work; GRB 050911: Page et al. (2006); Butler et al. (2007), this work; GRB 051105A: Barbier et al. (2005a); Butler et al. (2007), this work; GRB 051210: La Parola et al. (2006); Butler et al. (2007), this work; GRB 051211A: Donaghy et al. (2006); GRB 051221A: Golenetskii et al. (2005); GRB 051227: Hullinger et al. (2005); Sakamoto et al. (2005); Butler et al. (2007), this work; GRB 060121: Donaghy et al. (2006); Golenetskii et al. (2006a); GRB 060313: Roming et al. (2006); GRB 060502B: Sato et al. (2006a); Butler et al. (2007); GRB 060505: Hullinger et al. (2006), $E_{p,rest}$ computed according to equ. (3) of Liang et al. (2007b); GRB 060614: Mangano et al. (2007); Golenetskii et al. (2006b); Butler et al. (2007); GRB 060801: Sato et al. (2006b); Butler et al. (2007), this work; GRB 061006: Schady et al. (2006b); Golenetskii et al. (2006c); GRB 061201: Marshall et al. (2006); Golenetskii et al. (2006d); GRB 061210: Cannizzo et al. (2006); Urata et al. (2006); Butler et al. (2007); GRB 061217: Ziaeepour et al. (2007a); Butler et al. (2007); GRB 070209: Sato et al. (2007b); Butler et al. (2007), this work; GRB 070406: McBreen et al. (2007); Liang et al. (2007b); GRB 070429B: Markwardt et al. (2007b); Butler et al. (2007), this work; GRB 070707: Golenetskii et al. (2007b); GRB 070714B: Racusin et al. (2007); Ohno et al. (2007); GRB 070724: this work; GRB 070729: Golenetskii et al. (2007c); GRB 070809: this work; GRB 070810B: this work; GRB 071112B: this work.

References for host galaxy offset: In all cases where only an X-ray afterglow was detected, we used the XRT position from Butler (2007) and the associated webpage (http://astro.berkeley.edu/~nat/swift/xrt_pos.html) for newer GRBs (GRB 061210: v8.6; GRB 061217: v2.7; GRB 070429B: v0.7), except for GRB 051210, GRB 060801, GRB 070724 and GRB 070729, where we used XRT positions enhanced by UVOT astrometry (Goad et al. 2007) taken from the associated webpage (http://www.swift.ac.uk/xrt_positions/index.php). We note that in several cases where we could compare (GRB 050509B, GRB 051210, GRB 060502B) discrepancies on the $\approx 2\sigma$ level exist between Butler and Goad position, whereas in other cases (GRB 060801, GRB 070724) the error circles

overlap well. X-ray error circles are given at 90% confidence level, therefore, the offset errors are larger than 1σ confidence. Optical afterglow positions and host galaxy positions (or direct offsets) are taken from: GRB 050509B: Bloom et al. (2005); GRB 050709: Fox et al. (2005b); GRB 050724: Berger et al. (2005b); GRB 050813: Ferrero et al. (2007); GRB 051210: Berger et al. (2006b); GRB 051221A: Soderberg et al. (2006a); GRB 051227: Berger et al. (2006b); GRB 060121: Levan et al. (2006); GRB 060313: Berger et al. (2006b); GRB 060502B: Bloom et al. (2007a); GRB 060505: Ofek et al. (2007a); GRB 060614: Gal-Yam et al. (2006); GRB 060801: Piranomonte et al. (2006a); GRB 061006: Malesani et al. (2006b); Berger et al. (2006b); GRB 061201: D'Avanzo et al. (2006a); GRB 061210: Berger et al. (2006b); GRB 061217: Berger et al. (2006b); GRB 070429B: Cenko et al. (2008); GRB 070714B: Melandri (2007); Perley et al. (2007a); GRB 070724: Bloom (2007); GRB 070729: Berger & Kaplan (2007).

[a]Duration of the Initial Pulse Complex (IPC), identical to the complete GRB if no extended emission is detected.

[b]Identical to the low energy spectral index α in case of a fit with a power law plus exponential cutoff or a Band function fit.

[c]Total duration in case extended emission is observed at low energies.

[d]Extended emission only, total about 10 seconds more.

[e]Dominated by a short, hard spike of 0.25 s duration.

[f]For the short spike only; Barthelmy et al. (2005a) give $\Gamma = 1.38 \pm 0.13$ for the short spike, Campana et al. (2006) give $\Gamma = 1.75 \pm 0.16$ for the short spike, this softens to $\Gamma = 2.5 \pm 0.2$ afterward.

[g]Excluding low-level emission.

[h]Overlaid on a broader peak.

[i]Assuming $z = 0.5$.

[j]Assuming $z = 1$.

[k]Initial Pulse Complex only, the extended emission has several significant peaks too.

[l]Satellite: *S* = *Swift*, *K* = *Konus-Wind*, *H* = *HETE-2*, *Sz* = *Suzaku HXD-WAM*, *KA* = *Konus-A (Cosmos-2421)*,

[n]The radius of the XRT error circle is larger than the offset between the center of the error circle and the host galaxy center.

Table 2. Results on Type I GRBs

GRB	β^{a}	$A_V{}^{b}$	$dR_C{}^{c}$	mag[d]	$M_B(AG)^{e}$	k^{f}	$M_R(SN)^{g}$
050509B	0.6	0	+3.68	>28.95	> -13.9	$< 2.5 \times 10^{-3}$	> -12.7
050709	1.12	0.67	+4.15	25.3 ± 0.2	-17.6 ± 0.2	$< 1.5 \times 10^{-3}$	> -12.1
050724	0.76	0	+3.43	23.9 ± 0.1	-18.95 ± 0.13	< 0.06	> -16.1
050813	0.6	0	+0.81	>24.3	> -18.5	< 0.29	> -17.8
050906	0.6	0	+2.10	>28.0	> -14.8	< 0.08	> -16.4
050911	0.6	0	+4.41	>28.39	> -14.4	···	···
051105A[h]	0.6	0	+1.73	>25.15	> -17.7	···	···
051210	0.6	0	−0.83	>22.47	> -20.3	···	···
051211A[h]	0.6	0	+1.73	>23.43	> -19.8	···	···
051221A	0.62	0	+1.52	23.82 ± 0.2	-19.0 ± 0.2	< 0.60	> -18.6
051227[h]	0.6	0	+0.00	27.2 ± 0.5	-15.6 ± 0.5	···	···
060121[i]	0.6	0.5	−6.67	18.5 ± 0.5	-24.3 ± 0.5	···	···
060121[i]	0.6	1.1	−4.11	21.0 ± 0.3	-21.8 ± 0.3	···	···
060313[h]	0.6	0	+0.00	22.72 ± 0.07	-20.08 ± 0.07	···	···
060502B	0.6	0	+3.09	>27.28	> -15.5	$< 3.8 \times 10^{-3}$	> -13.1
060505	1.1	0	+6.16	26.6 ± 0.3	-16.2 ± 0.3	$< 3.3 \times 10^{-4}$	> -10.5
060614	0.41	0.28	+4.67	24.04 ± 0.05	-18.71 ± 0.05	$< 6.0 \times 10^{-3}$	> -13.6
060801	0.6	0	−0.31	>24.64	> -18.2	···	···
061006	0.6	0	+2.06	25.3 ± 0.2	-17.5 ± 0.2	···	···
061201	0.6	0	+5.32	28.9 ± 0.4	-13.9 ± 0.4	$< 4.8 \times 10^{-3}$	> -13.4
061210	0.6	0	+2.22	>25.6	> -17.2	···	···
061217	0.6	0	+0.47	>22.5	> -20.3	···	···
070209[h]	0.6	0	+1.73	···	···	···	···
070406[h]	0.6	0	+1.73	>26.0	> -16.8	···	···
070429B[h]	0.6	0	+0.26	>25.1	> -17.7	···	···
070707[h]	0.6	0	+1.73	24.84 ± 0.1	-18.0 ± 0.2	···	···
070714B[h]	0.6	0	+0.21	23.4 ± 0.3	-19.2 ± 0.35	···	···
070724	0.6	0	+1.95	> 26.9	> -15.9	···	···
070729[h]	0.6	0	+1.73	···	···	···	···
070809[h]	0.6	0	+1.73	26.0 ± 0.25	-16.8 ± 0.3	···	···
070810B	0.6	0	+1.78	> 27.0	> -15.8	···	···
071112B[h]	0.6	0	+1.73	> 26.6	> -16.2	···	···

[a]Excepting GRB 060121, if the slope is $\beta = 0.6$, then this is the assumed value.

[b]If the table gives extinction in the host frame as $A_V = 0$, then this is the assumed value, except for GRB 050724 and GRB 060505, where no extinction is found in the SED.

[c]The magnitude shift to $z = 1$.

[d]The R_c magnitude of the afterglow (or upper limit thereon) at 1 day after the GRB in the $z = 1$ frame.

[e]The absolute B-band magnitude of the afterglow at one day after the burst for $z = 1$.

[f]The upper limit on a supernova contribution. This has only been obtained for GRBs with deep late detections or upper limits (see Fig. 4). For the definition of k, see Zeh et al. (2004).

[g]The limit on the absolute R_c-band luminosity of a contributing supernova at peak.

[h]No redshift known. A shift $dRc = +1.73$ implies that we assume $z = 0.5$, a shift $dRc = +0.00$ implies we assume $z = 1$.

[i]For $z = 4.6$ (upper line) and $z = 1.7$ (lower line)

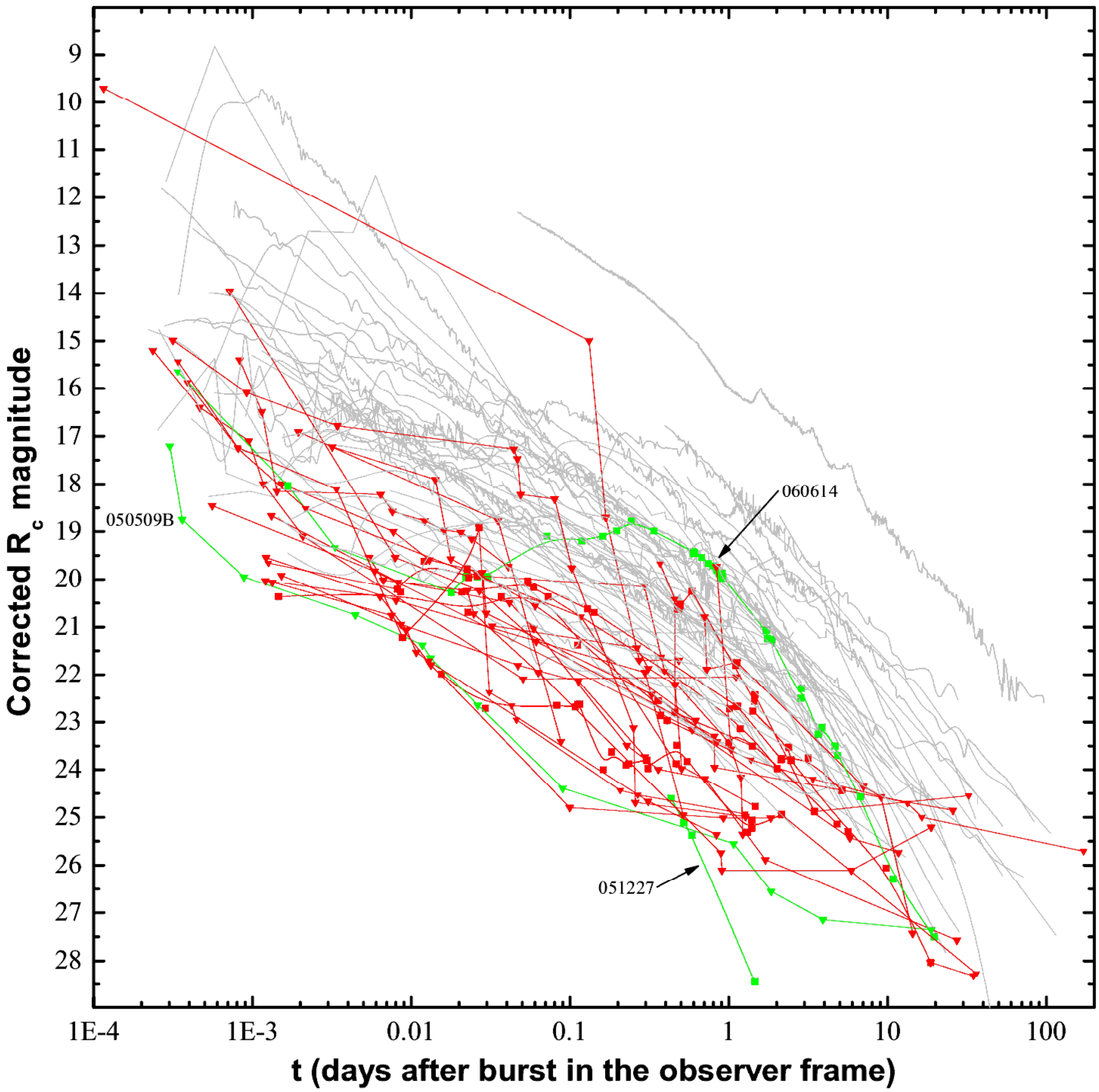

Fig. 1.— The afterglows of Type I and Type II GRBs in the observer frame. All data have been corrected for Galactic extinction and, where possible, the contribution of the host galaxy has been subtracted. Thin gray lines are Type II GRBs, taken from K06 and Paper I. Red lines with data points are upper limits (straight lines, downward pointing triangles) or detections (splines, squares) of Type I GRB afterglows. Several Type I GRB afterglows are highlighted in green. It is already clear from this figure that Type I GRB afterglows are fainter than Type II GRB afterglows, as most of the upper limits would have easily detected all Type II GRB afterglows presented here. The single detected Type I GRB afterglow that is comparable in brightness to the Type II GRB afterglow sample is that of GRB 060614.

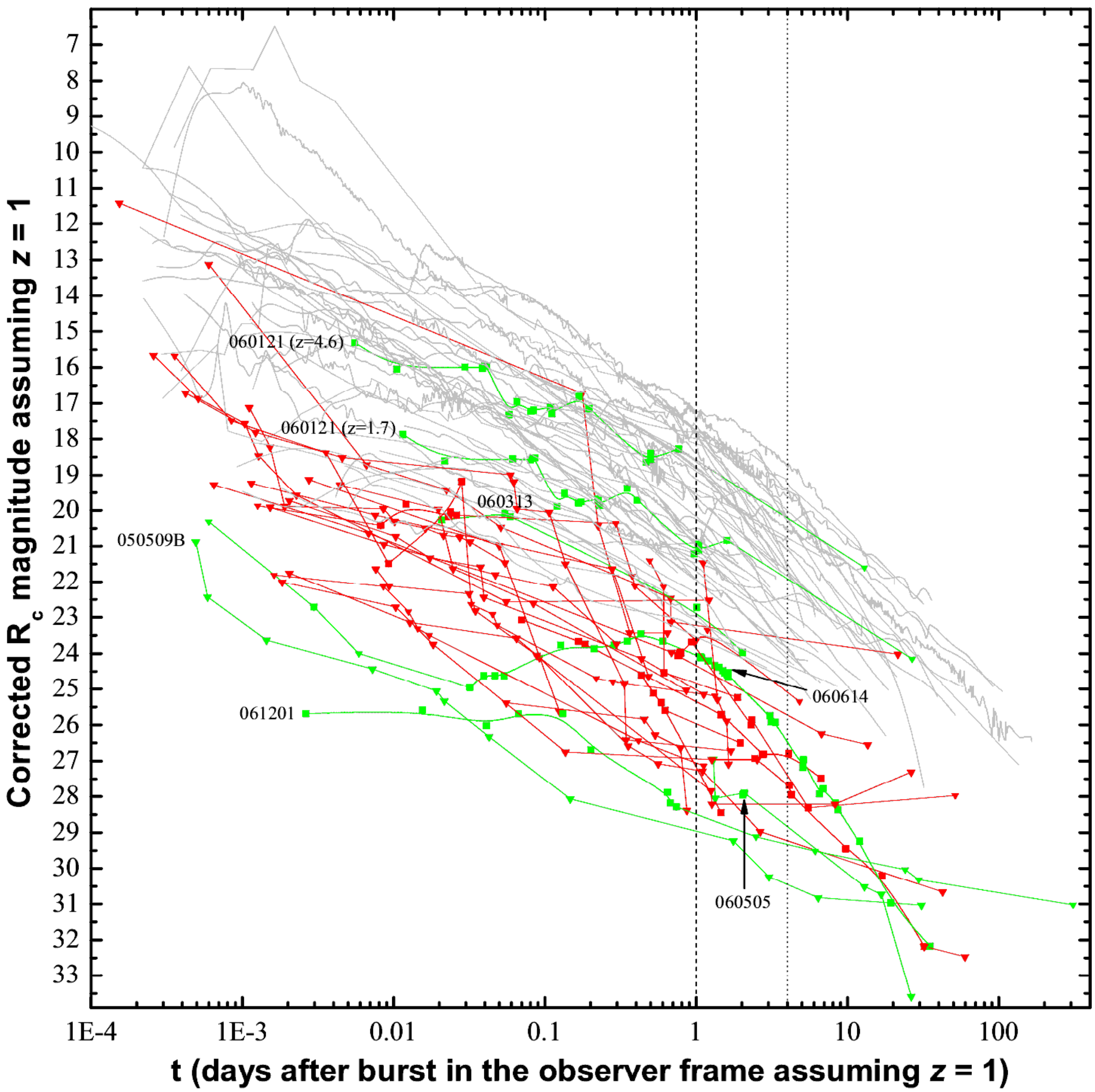

Fig. 2.— The afterglows of Type I and Type II GRBs in the observer frame after transforming all afterglows to $z = 1$. All additional *Swift* era afterglows fit into the tight clustering reported by K06, Liang & Zhang (2006), Nardini et al. (2006, 2008) and confirmed in Paper I. With the exception of the afterglow of GRB 060121, which is comparable to bright Type II GRB afterglows for $z = 4.6$ and faint Type II GRB afterglows for $z = 1.7$, all afterglows of Type I GRBs are fainter than those of Type II GRBs, including that of GRB 060614. The afterglow of GRB 060505, which is a unique, unclear case (§ 4.4), is extremely faint. The faintest early afterglow is that of GRB 061201, assuming $z = 0.111$ (Stratta et al. 2007). This is about 11 magnitudes fainter than the Type II GRB afterglows detected at this time. Assuming GRB 060121 to lie at $z = 4.6$, the total span at 1 day is more than 10 magnitudes, otherwise (GRB 060121 lies at $z = 1.7$), it is more than 7 magnitudes, still larger than the span of Type II GRB afterglows.

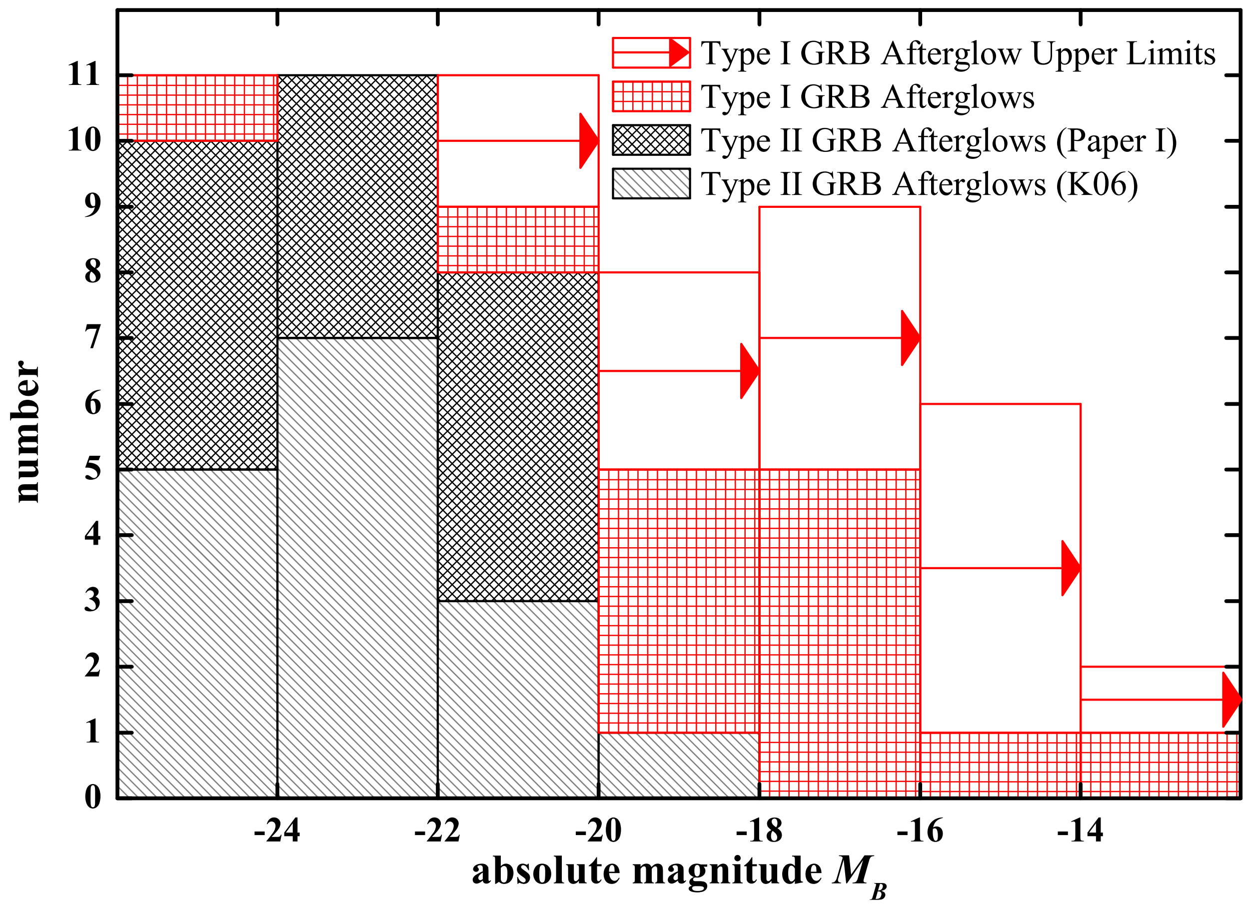

Fig. 3.— The absolute B-band magnitudes of Type II and Type I GRB afterglows or upper limits thereon. They are measured at one day after the burst in the observer frame after shifting the afterglow to $z = 1$. The Type I GRB afterglows are typically five magnitudes fainter than the type II GRB afterglows (mean magnitude $\overline{M_B} = -18.2 \pm 0.7$ versus $\overline{M_B} = -23.0 \pm 0.2$, respectively). The upper limits are even more constraining ($\overline{M_B} = \leq -17.0 \pm 0.5$). Note that some redshifts of the Type I GRB afterglow detection sample are estimates.

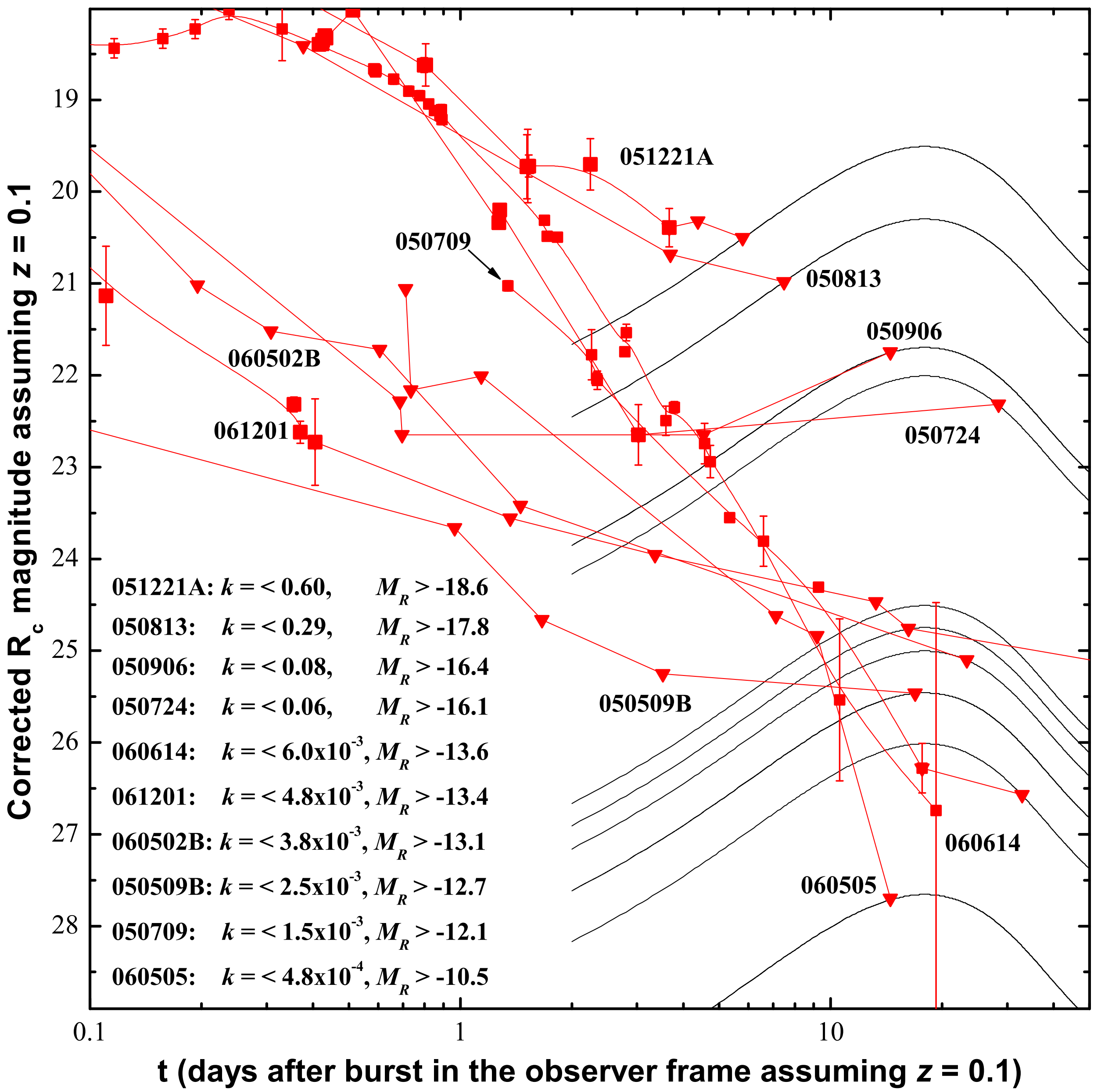

Fig. 4.— Deep late detections or upper limits of Type I GRB afterglows, all shifted to $z = 0.1$, and compared with the R-band light curve of SN 1998bw at $z = 0.1$. Here, we conservatively assume that the late detections derive from SN light only and there is no more afterglow contribution. For GRBs 051221A and 050813, the limits on an accompanying SN are not very strong, but all other Type I GRBs in this figure, including the temporally long events GRB 060505 and GRB 060614, give extremely stringent limits on any accompanying SN emission.

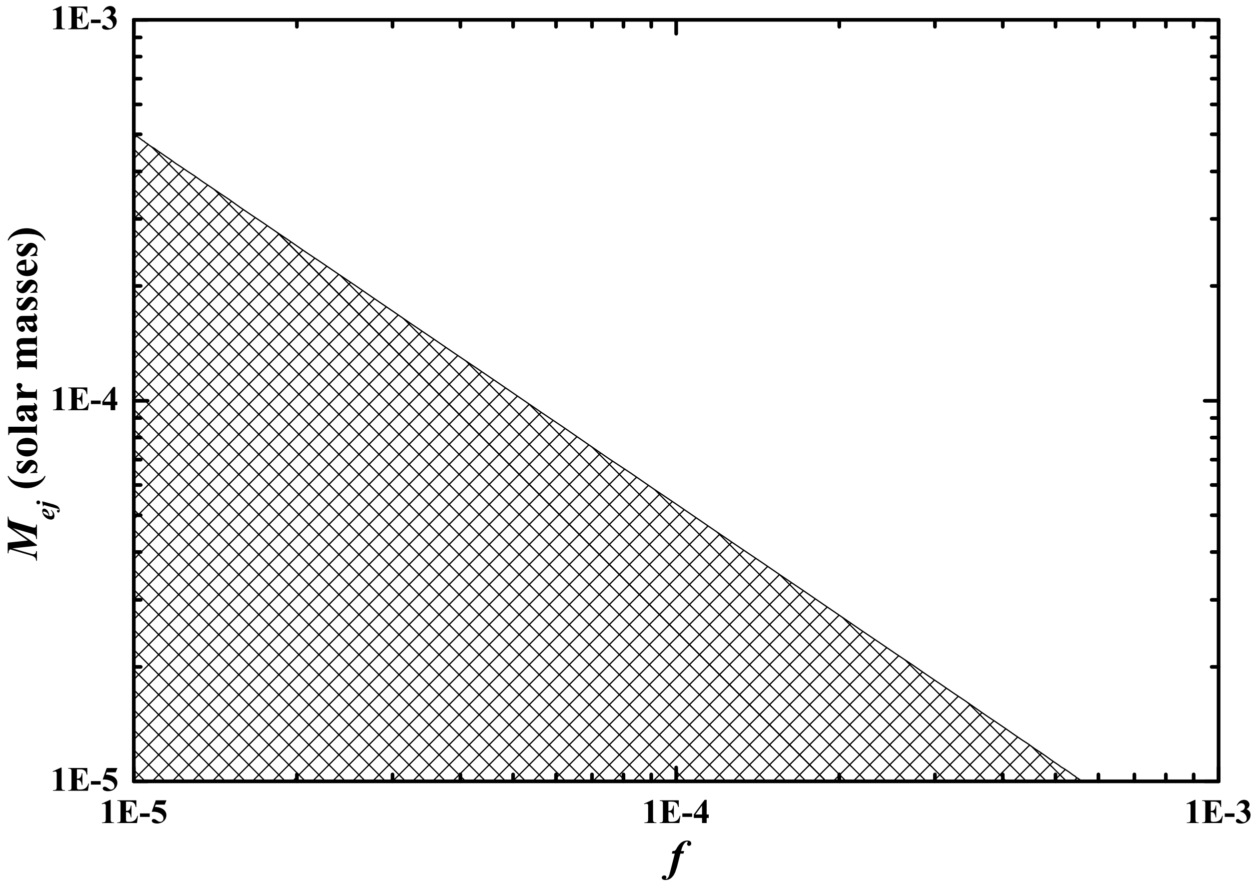

Fig. 5.— Constraints on the parameter space $(f, M_{\rm ej})$ of ejecta of the GRB 050509B assuming a heating source that decays according to a power-law. Shown here is the result obtained based on the observed upper limit of $R > 23.7$ at 0.96 days after the burst (see Fig. 4).

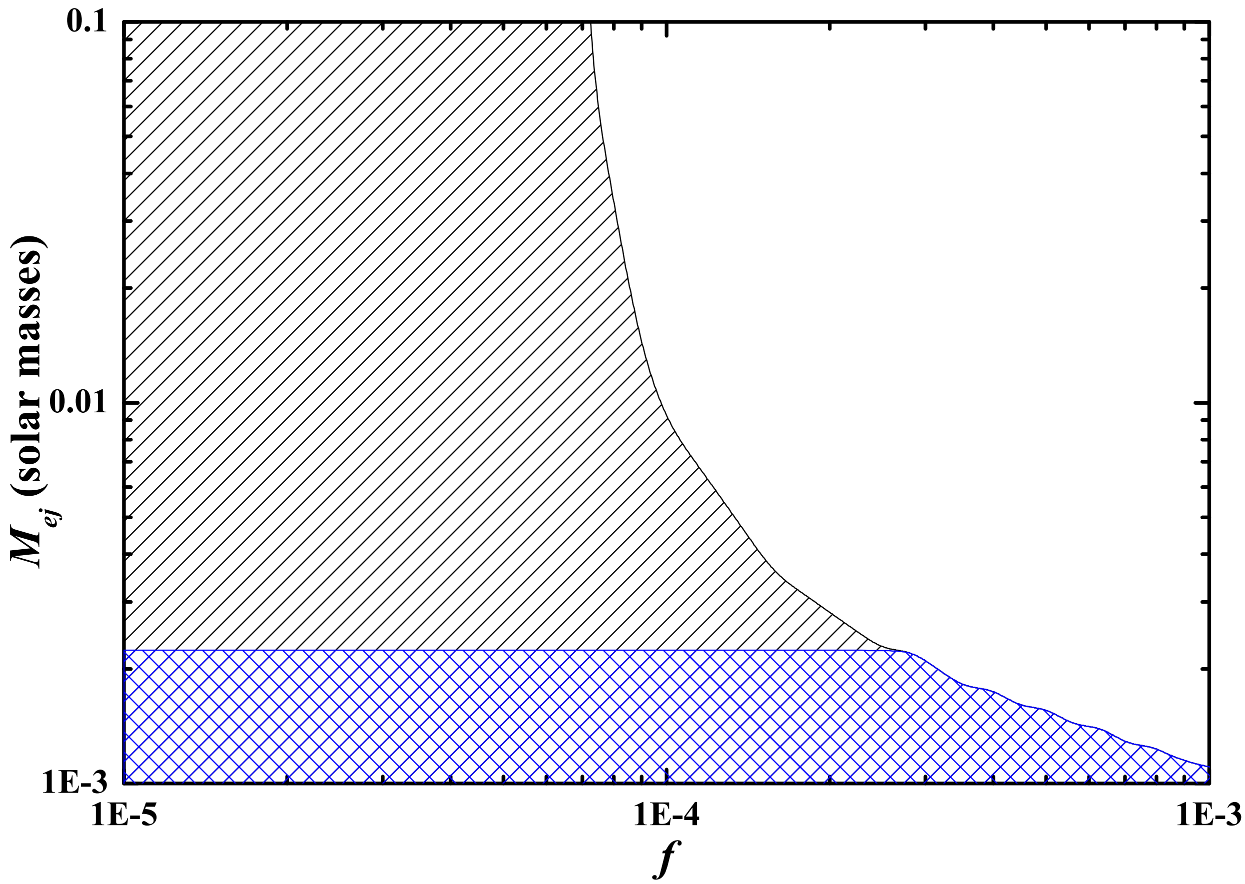

Fig. 6.— The same as Fig. 5 but assuming that the ejecta is heated by neutron decay. The blue, crosshatched region stands for cases where the ejecta is optically thin, so that the results obtained are less secure.

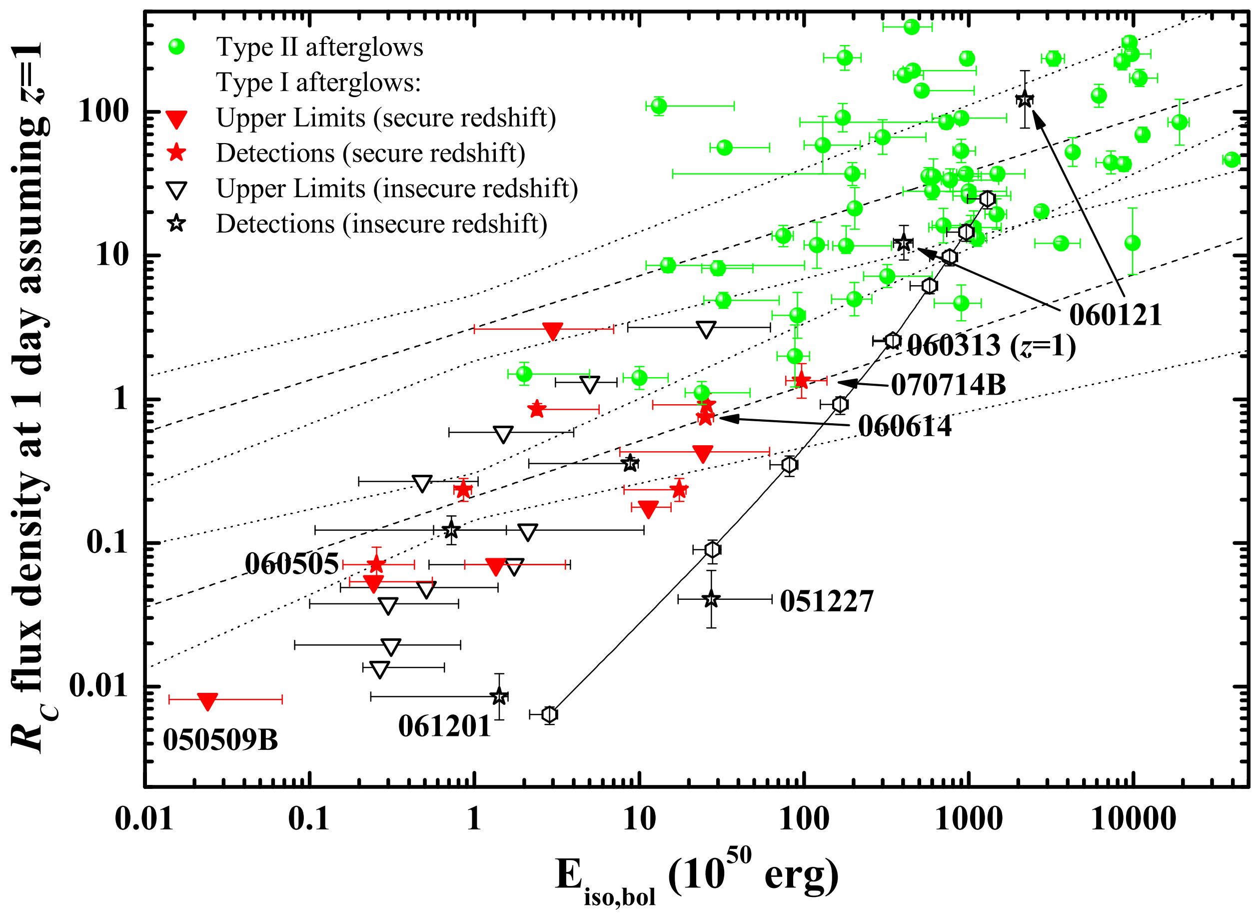

Fig. 7.— The R_C flux densities of the Type I and Type II GRB afterglows measured in the observer frame at one day after shifting the afterglows to $z = 1$ (Tables 2, Paper I, K06) plotted against the isotropic energy of the GRBs (Table 1 and Table 1 in Paper I). We differentiate between Type II GRB afterglows (green circles, Paper I), Type I GRB afterglow detections (stars) and upper limits (triangles). Type I GRBs with secure redshifts have filled red symbols, those with insecure redshifts have black open symbols. There is a clear trend visible. Bursts with higher isotropic energy tend to have more luminous afterglows at a fixed time. We also plot two unweighted fits (as well as their 1σ confidence intervals), one to the Type II sample (Paper I) and one to the Type I sample with detections and secure redshifts. Both fits have very similar slopes but a different normalization, indicating different typical circumburst densities. We also illustrate the effect of different redshifts (from $z = 0.1$, bottom, to $z = 2.0$, top) for GRB 060313. See text for more details.

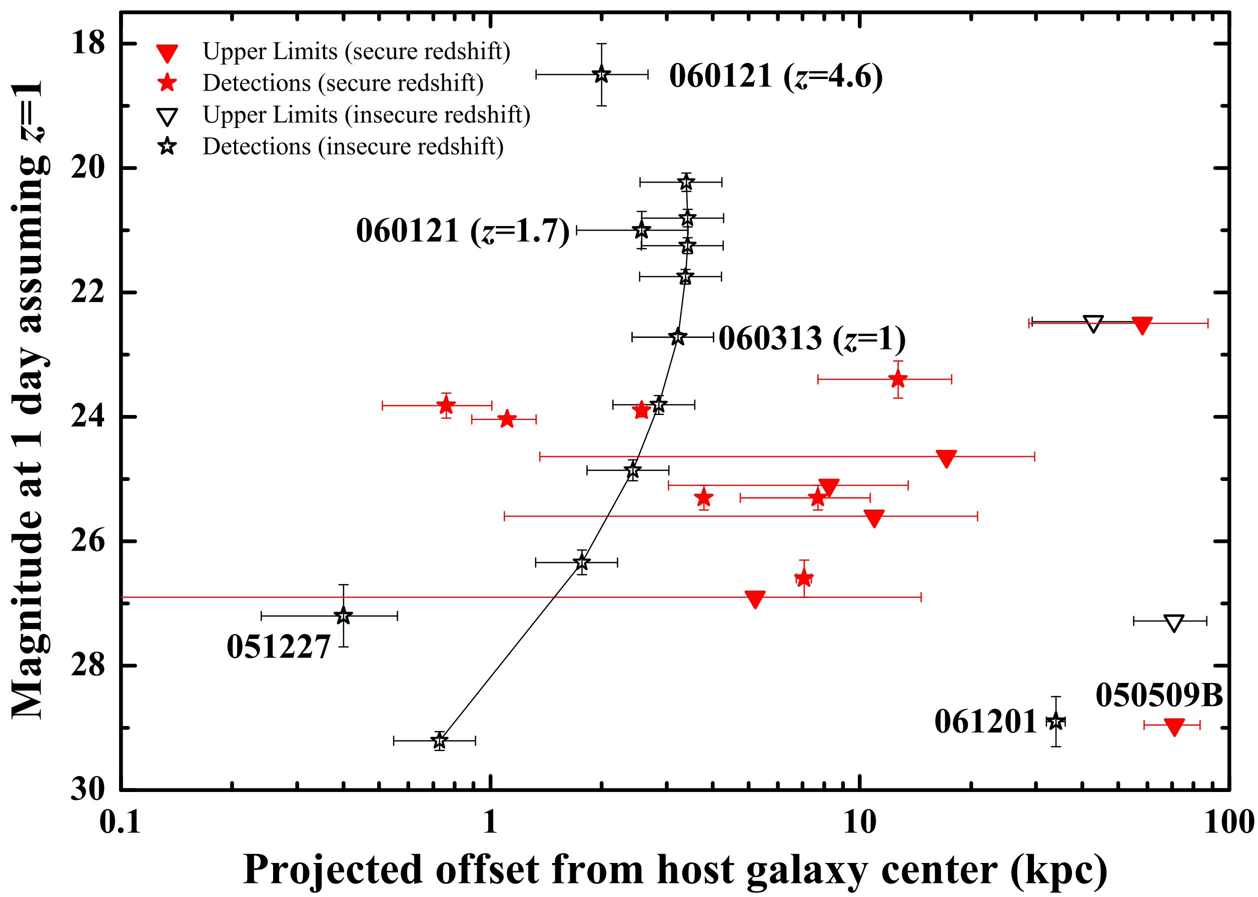

Fig. 8.— The magnitude of the Type I GRB afterglows measured in the observer frame at one day after shifting the afterglows to $z = 1$ (Table 2) plotted against the offset to the (assumed) host galaxy of the GRB (Table 1 in Paper I). The labeling is identical to Fig. 7. There is possibly a weak correlation between the two quantities, which could be expected, since larger offsets typically imply lower circumburst densities and thus lower afterglow luminosities. But there are strong outliers (with uncertain redshifts) such as GRB 051227 or the high redshift solution of GRB 060121. We illustrate the effect of different redshifts (from $z = 0.1$, bottom, to $z = 2.0$, top) for GRB 060313. Clearly, an uncertain redshift has a strong effect on the scatter of the correlation.

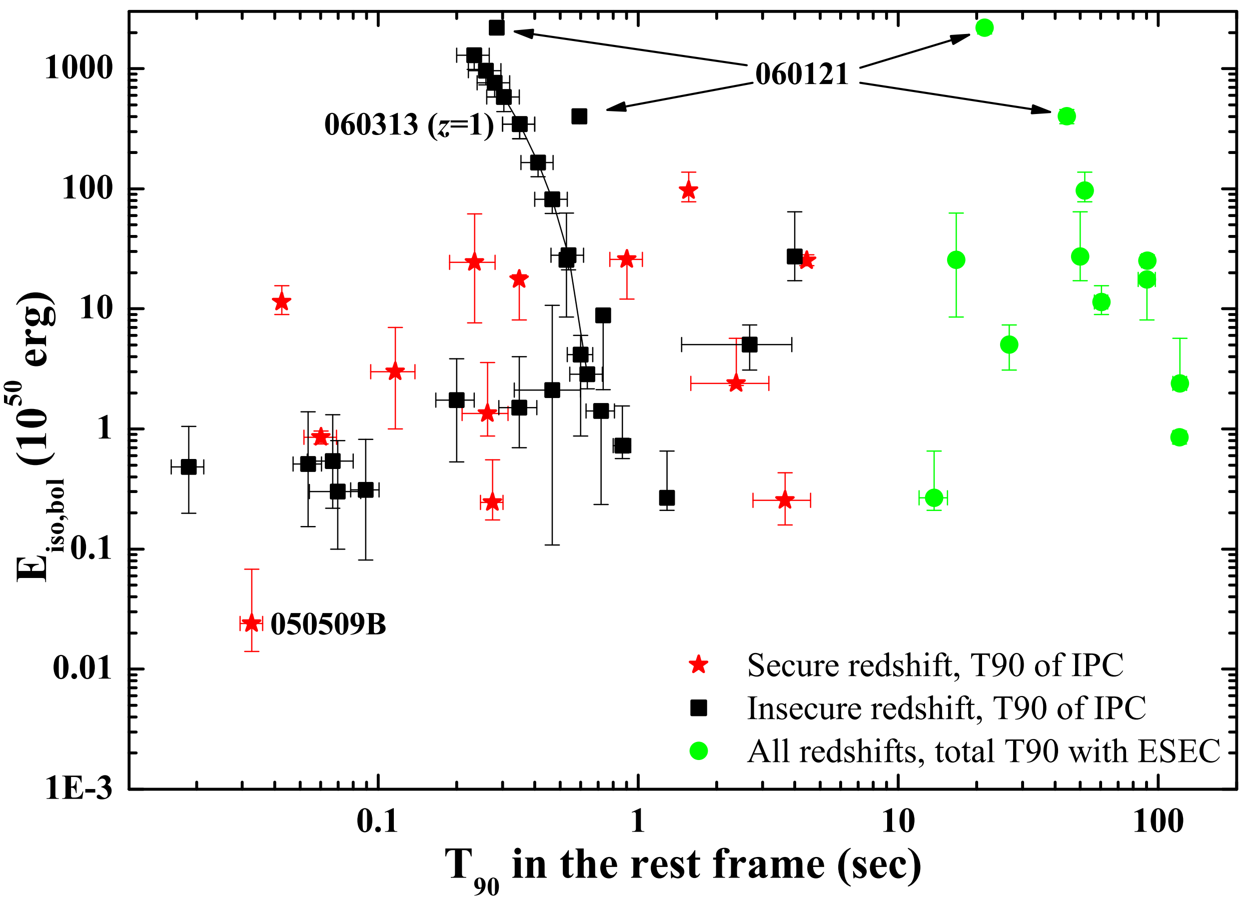

Fig. 9.— The bolometric isotropic energy of Type I GRBs plotted against the T_{90} of the Type I GRBs (Table 1). We differentiate between the duration of the Initial Pulse Complex (IPC) and the total duration in those cases where an Extended Soft Emission Complex (ESEC) exists (green circles). For the IPC T_{90}, we further differentiate between those GRBs with a secure redshift (red stars) and with an insecure redshift (black squares). While there is a trend visible, where longer GRBs have higher isotropic energies, it is not statistically significant. Once more, we illustrate the effect of different redshifts (from $z = 0.1$, bottom, to $z = 2.0$, top) for GRB 060313. Again, an uncertain redshift has a strong effect on the scatter of the correlation.

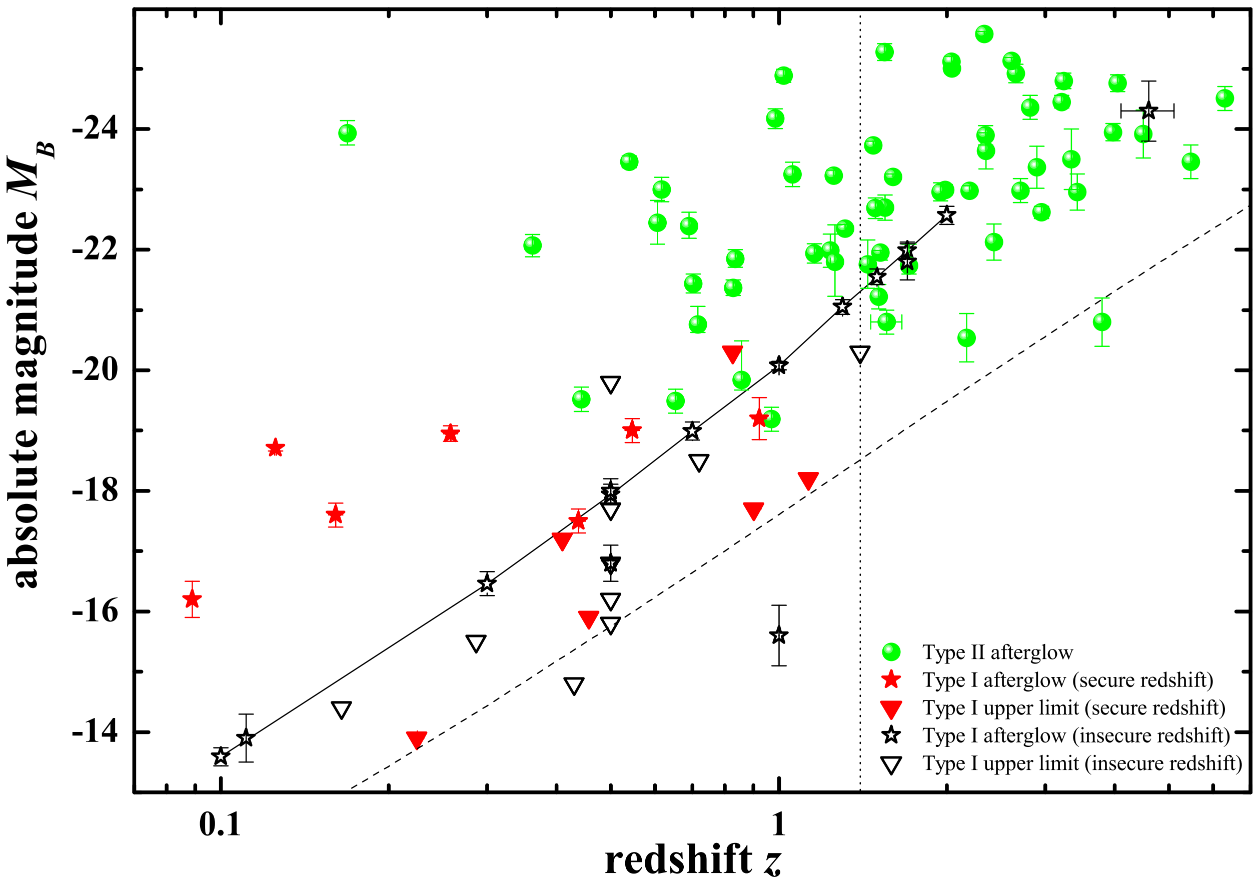

Fig. 10.— The absolute magnitude M_B of the Type I (Table 2) and Type II GRBs (Table 4 of Paper I) at one day assuming $z = 1$ versus their redshift z. A "zone of avoidance" for faint afterglows at high redshifts is visible, indicating a bias, both due to the detectors (telescope) and selection criteria. This is supported by plotting (dashed line) the line of constant observer frame luminosity, which parallels the detection edge. A strong outlier is GRB 051227 (assuming $z = 1$). In this case, the afterglow was only discovered due to very deep observations with 8m class telescopes. We plot the redshift track of GRB 060313, in this case, an uncertain redshift has almost no influence on the position compared to the detection edge. The vertical dotted line lies at $z = 1.4$ and denotes the separation between "type A" and "type B" GRBs (low-z and high-z, respectively, see K06). Clearly, with three exceptions (GRB 030329 at $z = 0.17$, GRB 071010A at $z = 0.99$ and GRB 991216 at $z = 1$), the nearby afterglows are fainter than the more distant ones. The very faint afterglow at $z = 3.8$ is GRB 050502A, which decayed rapidly (Yost et al. 2005).